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A minimum-time based fuzzy logic dynamic braking resistor control for sub-synchronous resonance

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Abstract

Dynamically switched resistor banks connected to the generator transformer bus are known to improve transient stability of the power system. In this article, a braking resistor control strategy designed through fuzzy logic control theory has been proposed to damp the slowly growing sub-synchronous resonant (SSR) frequency oscillations of a power system. The proposed control has been tested on the IEEE second benchmark model for SSR studies. A fuzzy logic controller designed through a classical minimum-time strategy was compared with a general fuzzy strategy employing generator speed variation and acceleration as input to the controller. It was observed that the proposed minimum-time based fuzzy controller provides better damping control; and it is computationally very efficient.

Keywords: Fuzzy logic control; Sub-synchronous resonance; Dynamic braking resistor

1. Introduction

A generating station is sometimes located very far from load centers, and is connected through long transmission distances. To raise the power limits of such lines, often they have to be capacitor compensated. The introduction of series capacitor in these long lines may give rise to low frequency resonant oscillations causing damage to the generator shafts. The resonant condition arising because of the interaction of the modes of the mechanical generator–turbine mass-spring system and the electrical network is termed as the sub-synchronous resonance (SSR).

The compilation of vast amount of literature by the IEEE Working Group on SSR studies demonstrates the keen interest of power engineers in the SSR phenomenon [1–3]. The measures proposed in the literature for countering SSR conditions are the excitation control, static VAR compensators, static phase-shifters, by-pass filter, etc. [4–7]. Use of dynamic braking resistors at the generator terminal to absorb the excess energy of the system under resonant condition has also been reported [8,9]. Determination of the instants of insertion and withdrawal of these devices for efficient control of SSR modes is, however, difficult.

The study of SSR phenomenon in power systems requires a very high order dynamic modeling. Optimal determination of switching strategies for braking resistors from such a model would be a formidable job, if not impossible. Fuzzy logic control theory offers good potential for such control designs. In Fuzzy logic control design of continuous processes, the available expert knowledge about the plant variables are converted to fuzzy variables and compared with the fuzzy states of the system to arrive at the fuzzy decision variable. This fuzzy information is then defuzzified and fed to the plant. The intelligent decision can come from operator field experience, system simulation studies, etc. A good fuzzy design for the dynamic brake control should be effective in terms of transient control, and at the same time it should be simple and computationally efficient from implementation viewpoint. To the best of author's knowledge, application of fuzzy braking resistor control for damping the SSR modes have not been reported in the literature.

This article presents a fuzzy logic controller design for switching of the braking resistors. The intelligent decision required for the fuzzy controller is based on a classical minimum-time strategy for power system damping control. Inclusion of the time-optimum strategy in the design also reduces the number of fuzzy variables. The IEEE second benchmark model for SSR studies was simulated with the proposed fuzzy controller and the response compared with a general fuzzy scheme. The response obtained with the proposed fuzzy controller has been observed to provide excellent SSR control.

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2. The power system model for SSR studies

The IEEE second benchmark power system model for SSR studies [4,10], shown in Fig. 1, is considered in this article The system consists of a synchronous generator feeding an infinite bus over two parallel transmission lines, one of which is capacitor compensated. The dynamic resistor brake is connected to the high-voltage side of the generator transformer. The mechanical part of the generating unit is a mass-spring system containing four masses which are high-pressure turbine, low-pressure turbine (LP), generator (G), and the exciter all coupled on the same shaft.

The dynamic model of the generator and its control elements, the capacitor-compensated transmission line, mechanical mass-spring system of the generator–turbine units is expressed in the form

$$\dot{x} = f[x, u] \tag{1}$$

Here, x is the state vector and control u is the power absorbed by the resistor brake.

For small perturbations of the states, the system of Eq. (1) can be linearized around the steady state equilibrium point and expressed as

$$\Delta\dot{x} = A\Delta x + Bu \tag{2}$$

The matrix A in the above equation depends on the degree of series capacitor compensation. The compensation factor, given as X_C/X_L, is the ratio between capacitor and transmission line reactances. The eigenvalue of matrix A corresponding to the electromechanical oscillations is termed mode 0, while the other sub-synchronous modes in ascending order are termed modes 1, 2, and 3. Fig. 2 shows that at lower values of capacitor compensation the electromechanical mode (mode 0) is unstable. This is expected for a weakly connected power system. With the increase in compensation, the real part of the electromechanical mode starts to decrease, while that of mode 1 starts to increase. At 56% capacitor compensation, mode 1 has the largest real part. The sub-synchronous oscillations in the power system arise when this mode is excited by a disturbance in the system.

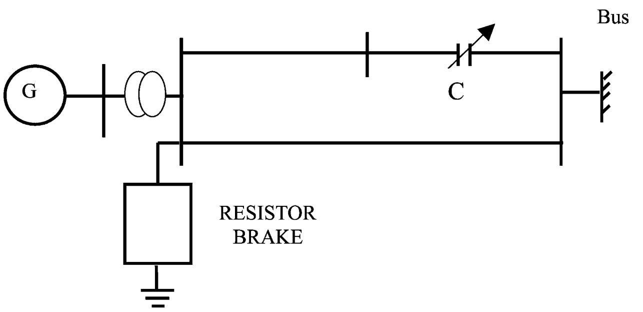

Fig. 1. IEEE second benchmark model with resistor brake.

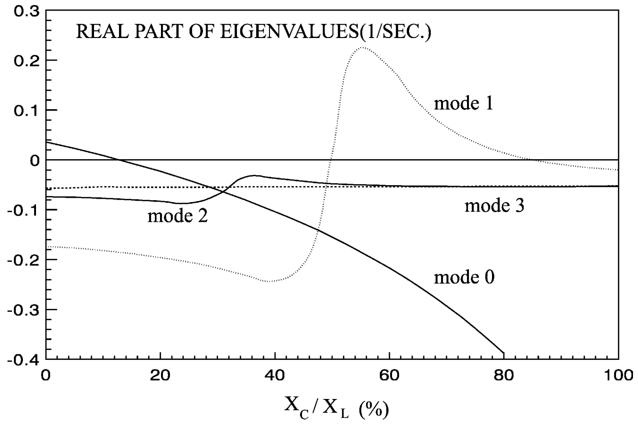

Fig. 2. Real part of the eigenvalues of the sub-synchronous modes against degree of compensation.

3. The fuzzy logic dynamic brake control

Fig. 3 shows the configuration of a fuzzy logic control system that is employed for designing the fuzzy resistor brake controller. The knowledge base contains information about all the input and output fuzzy partitions. It will include the term set and the corresponding membership functions defining the input variables to the fuzzy 'rule-base' system and the output or decision variables to the plant [11]. The crisp stabilizing input signals are converted to fuzzy linguistic variables in the fuzzifier. These are then composed with the fuzzy decision variables. The decision-making logic generates the fuzzified control through various composition rules. The fuzzy control is then defuzzified and the decision is used whether the braking resistor should be switched in or out. The following steps are involved in designing the fuzzy dynamic brake controller [11–14].

1. Choose the inputs to the fuzzy dynamic brake controller. The inputs considered for controller design are the change in generator angular speed ($\Delta\omega$) and acceleration ($\Delta\alpha = \Delta\dot{\omega}$). The decision variable is the brake power.
2. Choose membership functions to represent the inputs in fuzzy set notation. Triangular functions are chosen in this work. For example, fuzzy representation of generator speed deviation ($\Delta\omega$) is shown in Fig. 4. Linguistic variables chosen are large positive (LP), medium positive (MP), small positive (SP), very small (VS), small negative (SN), medium negative (MN), and large negative (LN) at thresholds s_1, s_2, s_3, 0, s_4, s_5, s_6, respectively. Similar membership functions for the output are also defined.
3. A set of decision rules relating the inputs to the controller with the output are compiled and stored in the memory in the form of a 'decision table'. A set of rules constructed to provide damping control for a power system with ($\Delta\omega - \Delta\alpha$) input is entered in the form of a decision table (Table 1). The first entry in the table is read as,

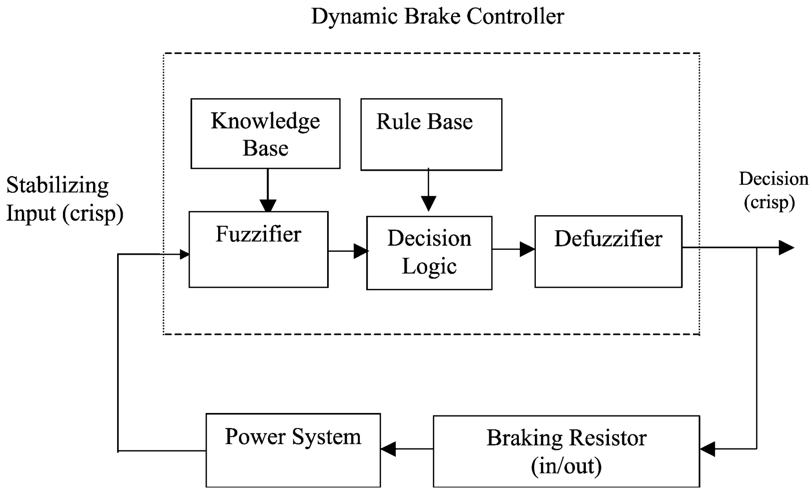

Fig. 3. Fuzzy logic controller block diagram.

IF $\Delta\omega$ is large negative (LN), AND $\Delta\alpha$ is large negative (LN); THEN control (u) is large negative (LN).

4. For N linguistic variables for each of $\Delta\omega$ and $\Delta\alpha$, there are N^2 possible combinations resulting into any of M values for the decision variable u. All the possible combinations of inputs, called states, and the resulting control are then arranged in a $(N^2 \times M)$ 'fuzzy relationship matrix' (FRM). For triangular membership functions of all the linguistic variables, a partial FRM is shown in Table 2.
5. The membership values for the output characterized by the M linguistic variables are then obtained from the intersection of the N^2 values of membership function $\mu(x)$ with the corresponding values of each of the decision variables in the FRM.
6. The fuzzy outputs are then defuzzified to obtain crisp u. The method of weighted average [11] has been employed in this work.

4. The control strategies

Two different fuzzy control strategies are presented in this article. They are:

1. A general fuzzy rule-based controller depending on the general expert information on power system stability that brakes switched in according to the variations of states like generator rotor speed deviation and acceleration can effectively provide damping to a power system.
2. A fuzzy logic control strategy that employs a classical optimum strategy to gather the expert information for the control to stabilize the sub-synchronous oscillations in minimum-time.

4.1. The general fuzzy controller design

Generator speed deviation ($\Delta\omega$) and acceleration ($\Delta\alpha$) feedback signals are generally known to provide damping to power system and have been extensively used in designing controllers for excitation control, static VAR compensators, etc. The expert knowledge used in the general controller design is that if the states are far from the origin, exertion of large control is required. The amount of brake control is decided approximately by the location of the states in the $\Delta\omega - \Delta\alpha$ space. For each of

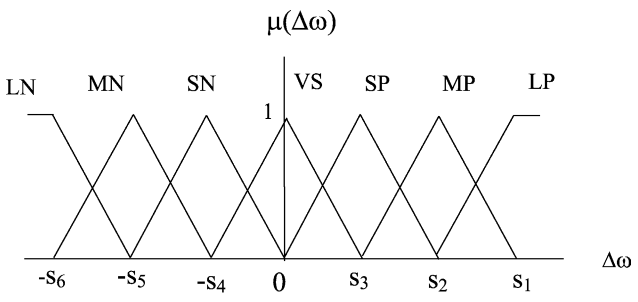

Fig. 4. Linguistic variables and membership functions for speed signal.

Table 1
Decision table in angular speed deviation–acceleration space

$\Delta\omega$	$\Delta\alpha$						
	LN	MN	SN	VS	SP	MP	LP
LN	LN	LN	LN	LN	MN	SN	VS
MN	LN	LN	MN	MN	SN	VS	SP
SN	LN	MN	SN	SN	VS	SP	MP
VS	MN	MN	SN	VS	SP	MP	MP
SP	MN	SN	VS	SP	SP	MP	LP
MP	SN	VS	SP	MP	MP	LP	LP
LP	VS	SP	MP	LP	LP	LP	LP

Table 2
Fuzzy relationship matrix for the triangular membership functions

Controller input		Controller output						
x_i	$(\Delta\omega, \Delta\alpha)$	LN Membership values	MN	SN	VS	SP	MP	LP
		$\mu_R(x_1, \mathrm{LN})$	$\mu_R(x_1, \mathrm{MN})$	$\mu_R(x_1, \mathrm{SN})$	$\mu_R(x_1, \mathrm{VS})$	$\mu_R(x_1, \mathrm{SP})$	$\mu_R(x_1, \mathrm{MP})$	$\mu_R(x_1, \mathrm{LP})$
x_1	(LN,LN)	1	0.5	0	0	0	0	0
x_2	(LN,MN)	1	0.5	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
x_{24}	(VS,SN)	0	0.5	1	0.5	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
x_{48}	0	0	0	0	0	0	0.5	1
x_{49}	0	0	0	0	0	0	0.5	1

the inputs $\Delta\omega$, $\Delta\alpha$, and the controller output u, seven linguistic variables LP, MP, SP, VS, SN, MN, and LN are chosen. The whole $\Delta\omega - \Delta\alpha$ space is mapped with decision (control) variables obtained from expert information. The controls for all possible inputs are entered in a decision table (Table 1).

The FRM is constructed out of the 49 possible input combinations, called states, against seven possible decisions in a 49×7 matrix. For triangular membership functions for all the linguistic variables, part of the FRM is shown in Table 2. The choice of seven linguistic variables and the nature of membership functions have been employed in several power system control studies [13,14].

4.2. Generation of expert information from a classical minimum-time strategy

To include the optimality criterion in the fuzzy decision process, control derived from a closed loop quasi-optimum stabilizing strategy is incorporated in the decision-making logic. The optimum control problem for stabilization of a power system followed by a perturbation can be stated as: given the system of Eq. (1), find control u, which brings the power system from any initial state x_0 to one of its stable equilibrium points following the disturbance and minimizing an appropriate performance index. For non-linear system equations (Eq. (1)) there is no straightforward solution. The optimum control for the linearized system (2) can be obtained by LQR [15] or similar other methods. However, such a solution is operating point dependent.

A classical quasi-optimum strategy for the braking resistor controller u, which damps the SSR oscillations in minimum-time presented in Ref. [10] gives the control strategy as

$$u = \begin{cases} 1 & \text{(braking resistor on) if } \Sigma \geq 0 \\ 0 & \text{(braking resistor off) if } \Sigma < 0 \end{cases} \tag{3}$$

The derivation given in Appendix A shows that the switching function Σ depends on weighted value of generator rotor angle (δ), speed deviation ($\Delta\omega$), and the generator power unbalance ΔP of the generator. In the absence of any constraint on δ, the braking strategy depends on speed variation $\Delta\omega$ of the generator alone. The switch curve Σ shown in Fig. 5 divides the $\delta - \Delta\omega$ plane into two regions R^+ and R^-. The brake control is positive in R^+ and negative in R^-, and control switches at $\Sigma = 0$. The quasi-optimum scheme gives the control as a bang–bang function. For realization on a real system it can be made proportional to the switching function by multiplying with an appropriate gain function. The control is derived from a continuously updated reduced order model, which is not strictly optimal but can be stated as 'quasi-optimum'. However, this gives very important information for the application of the fuzzy analysis presented in Section 4.3. Note that no approximations have been made in the dynamics (1) in the simulation studies.

4.3. Minimum-time based fuzzy decision process

Fig. 5 shows that control is clearly positive in the first quadrant, while it is negative in the third. The transition of the control occurs in the second and fourth quadrants. The switch curve Σ is not fixed in the $\delta - \Delta\omega$ plane because of its

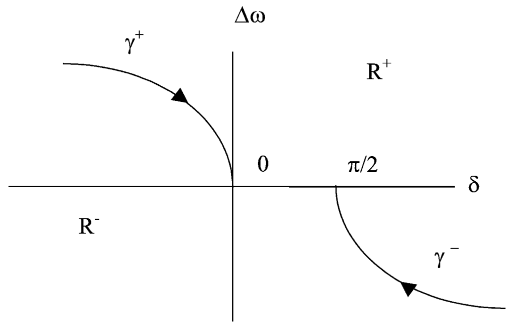

Fig. 5. Approximate switch curves for minimum-time brake control.

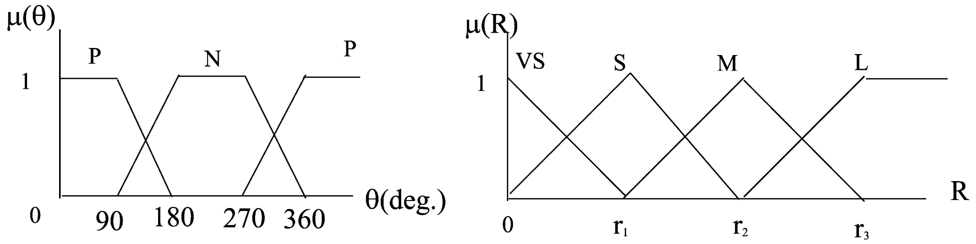

Fig. 6. Linguistic variables and membership functions based on minimum-time strategy.

dependence on the quantity ΔP, and hence the control in these regions is fuzzy. It has been observed that for normal operating ranges the switch curves are restricted to a small region in the second and fourth quadrants. If the $\Delta\delta - \Delta\omega$ plane is converted to the polar $R-\theta$ plane through the relation,

$$R = [(\Delta\delta)^2 + (\beta{\cdot}\Delta\omega)^2]^{1/2};\ \theta = \tan^{-1}(\beta{\cdot}\Delta\omega/\Delta\delta) \quad (4)$$

it can be seen that θ and R can be described by the fuzzy notations given in Fig. 6. A scaling factor β is introduced to make the membership functions in Fig. 6 symmetric.

Since the distance R is a positive quantity, four linguistic variables large (L), medium (M), small (S), and VS are adequate to represent it. Also, only two linguistic variables, positive (P) and negative (N), are required to represent the decision in terms of θ. The decision table and the FRM are presented in Tables 3 and 4, respectively. The decision tables and FRM for the proposed minimum-time based fuzzy brake controller are 4×2 and 8×7 matrices, respectively. Note that the same seven control variables are used in this formulation also.

5. Simulation results

The IEEE benchmark model for SSR studies shown in Fig. 1 was simulated in this study. The dynamic model for the system was represented by a 21st order non-linear set of differential equations, eight equations relating the voltage–current–flux for the generator circuits, eight for turbine–generator mass-spring system, two for the series compensated line, and three equations to represent the generator exciter system. A 20% input torque pulse for four cycles was simulated as the disturbance. For 56% capacitor compensation the worst torsional torque was observed between the low-pressure turbine and generator (LP–G) section of the shaft. Fig. 7 shows this (LP–G) torsional torque variation, angular speed change, and terminal voltage variation of the generator in the absence of any stabilizing control. The response is very slowly growing indicating that a sub-synchronous mode has been excited by the disturbance. Fig. 8 shows the response when classical minimum-time control derived in Section 4.2 is applied. This serves as a basis for comparison of the transient responses obtained with the following fuzzy algorithms.

5.1. The general fuzzy dynamic brake controller

Fig. 9 shows the LP–G torsional torque and generator speed variations with the general fuzzy dynamic braking algorithm employing $\Delta\omega - \Delta\alpha$ as the input to the controller. Since the brake power can only be positive, the negative values generated by the control algorithm are set to zero. Maximum brake output of 0.1 pu is considered in these studies. Comparison of the responses exhibited in Figs. 7–9 shows that the fuzzy logic control with speed deviation and acceleration inputs provides good damping to the SSR oscillations.

5.2. Minimum-time based fuzzy control

Fig. 10 shows the LP–G torque and generator angular speed variations with the minimum-time based fuzzy

Table 3
Decision variables in terms of R and θ

R	θ	
	P	N
VS	VS	VS
SP	SP	SN
MP	MP	MN
LP	LP	LN

Table 4
Fuzzy relationship matrix constructed from Table 3

Input	Controller output						
	LN	MN	SN	VS	SP	MP	LP
x_1(VS, P)	0	0	0.5	1	0.5	0	0
x_2(VS, N)	0	0	0.5	1	0.5	0	0
x_3(SP, P)	0	0	0	0.5	1	0.5	0
x_4(SP, N)	0	0.5	1	0.5	0	0	0
x_5(MP, P)	0	0	0	0	0.5	1	0.5
x_6(MP, N)	0.5	1	0.5	0	0	0	0
x_7(LP, P)	0	0	0	0	0	0.5	1
x_8(LP, N)	1	0.5	0	0	0	0	0

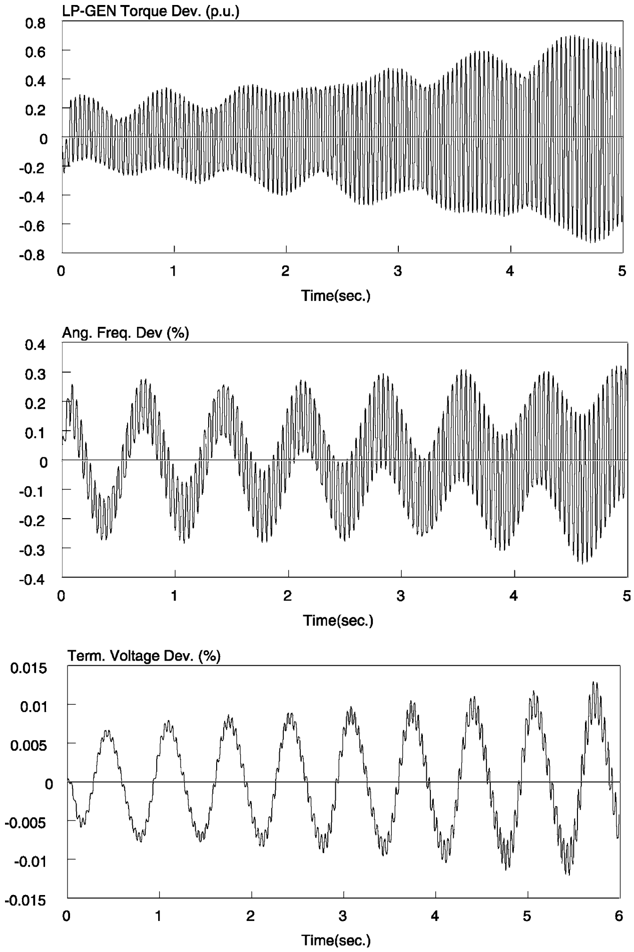

Fig. 7. LP–G torsional torque, generator angular frequency, and terminal voltage variations following a 20% torque pulse for four cycles in the absence of any stabilizing control.

control strategy of Section 4.3. Fig. 11 gives a comparison of the terminal voltage variations with the general fuzzy dynamic brake control with the crisp-optimum based fuzzy control. Fig. 12 gives the comparison of the control signals from the general fuzzy scheme with the proposed minimum-time based fuzzy strategy. Because of the ‘bang–bang’ nature of the control signal in the general fuzzy scheme as shown in Fig. 12(a), there may be small steady state error in the response. The transition is smooth in the proposed minimum-time based fuzzy controller because of the inclusion of a proportionality parameter in the switching algorithm.

From comparison of the various results presented it can be observed that the minimum-time based fuzzy logic controller gives better transient response compared to the non-optimum general fuzzy case. The minimum-time based fuzzy algorithms is superior to the classical control because it is robust, does not depend on system states as the classical time-optimum one, and at the same time the optimality condition is embedded in it. When compared with the general fuzzy strategy, the proposed minimum-time based fuzzy algorithm is extremely efficient computationally

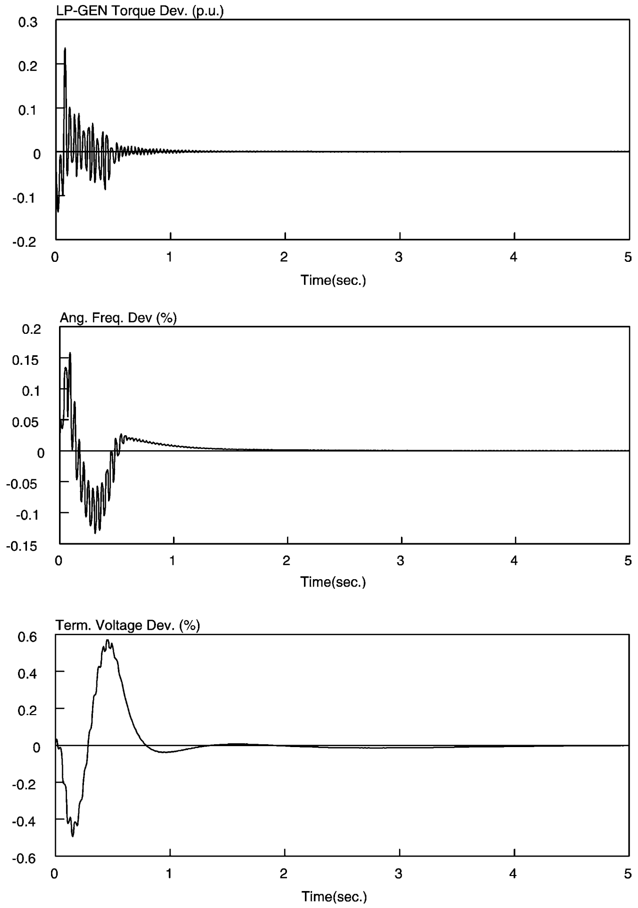

Fig. 8. LP–G torsional torque, generator angular frequency, and terminal voltage variations corresponding to Fig. 7 with classical minimum-time crisp control.

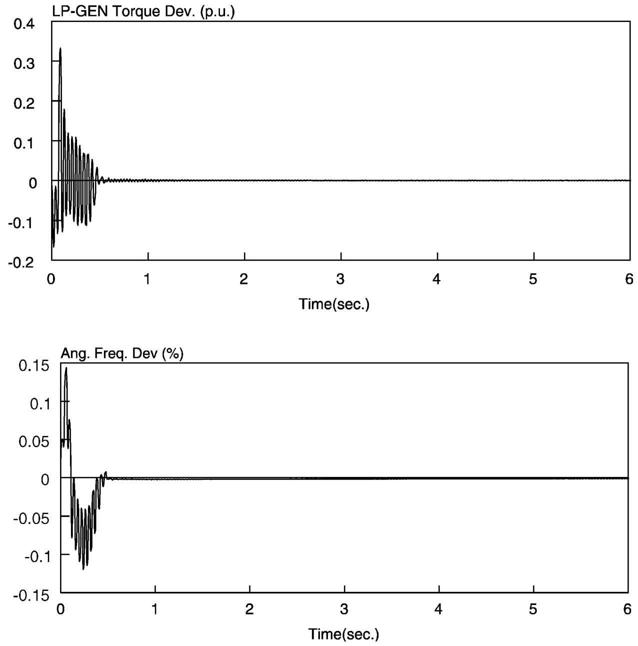

Fig. 9. LP–G torsional torque and generator angular frequency, and terminal voltage variations with general fuzzy logic control.

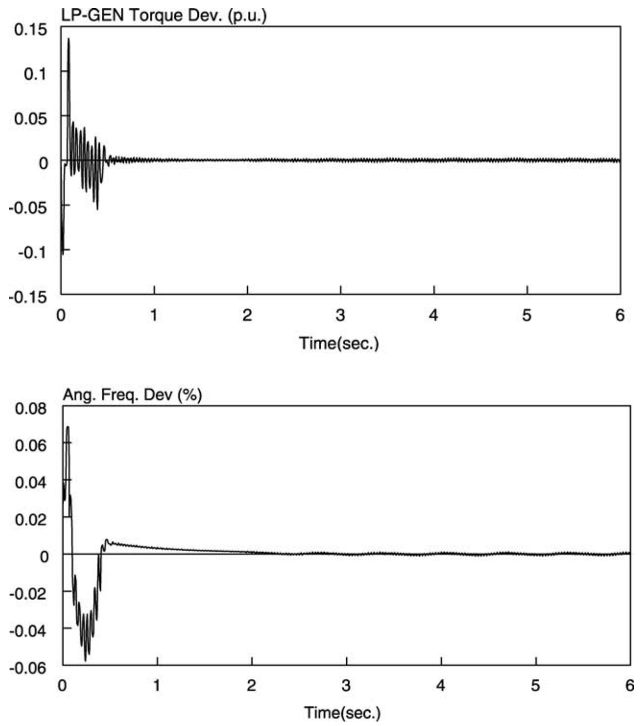

Fig. 10. LP−G torsional torque and angular frequency variations with the proposed minimum-time based fuzzy control.

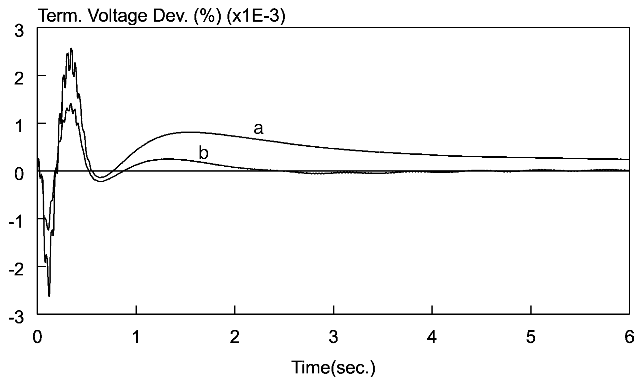

Fig. 11. Comparison of terminal voltage variation characteristics with: (a) general fuzzy brake control and (b) the proposed minimum-time based fuzzy control.

(compare decision tables of 7 × 7 with 4 × 2, and FRM of 49 × 7 with 8 × 7).

6. Conclusions

A fuzzy logic dynamic braking resistor controller has been designed, which combines the classical optimum control theory for stabilization of power systems with fuzzy control logic. The control has been tested on the IEEE second benchmark model for SSR studies. The transient response of the power system with the proposed minimum-time based fuzzy controller has been compared with a general fuzzy strategy used for damping of power system SSR oscillations. It has been observed that the minimum-time based fuzzy controller provides excellent damping control. The proposed method embeds an optimization procedure for damping control in it and, naturally, is superior to the conventional non-optimum fuzzy designs.

The proposed minimum-time based fuzzy algorithm is also computationally very efficient because it involves significantly less number of fuzzy variables. One of the difficulties of on-line application of fuzzy strategies is that the computational time requirement is, generally, more than plant real-time. It is hoped that the significant reduction in computation with the proposed algorithm will make fuzzy logic control a step closer to real-time application.

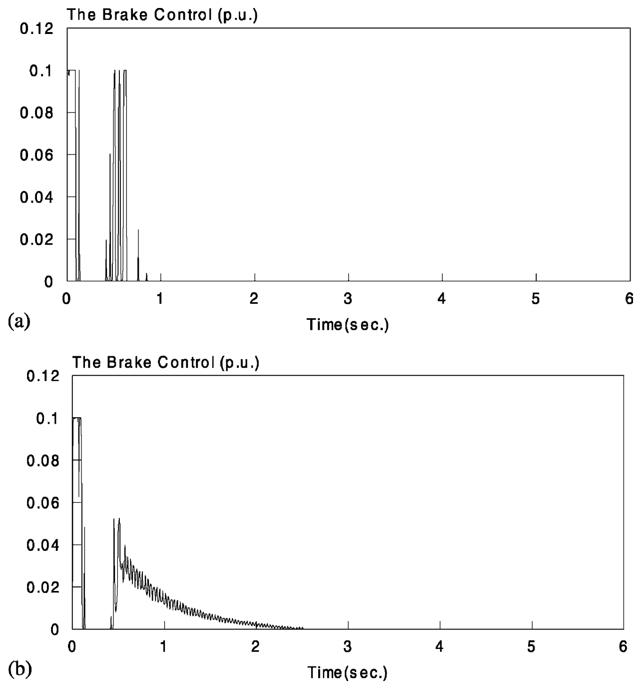

Fig. 12. Control signal with: (a) general fuzzy logic algorithm and (b) proposed minimum-time based fuzzy algorithm.

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Appendix A

Consider the electromechanical swing equation of the generator included in the general dynamics Eq. (1) for the single machine system. This is rewritten as

$$M\ddot{\delta} = P_{\mathrm{m}} - P_{\mathrm{e}} - \mathrm{P}_b \tag{A1}$$

where P_m and P_e are the mechanical power input and electrical power output of the generator, respectively. P_b is the power output of the brakes, which represents control in Eq. (A1). The above can be rewritten as

$$\ddot{\delta} = b\Delta P + bu \tag{A2}$$

Here, b is the reciprocal of inertia constant, and ΔP is the difference between P_m and P_e. The power absorbed by the brake can vary from 0 to a maximum, say 1; hence the constraint on the control variable can be written as

$$0 \le u \le 1 \tag{A3}$$

Since one of the main objectives in stabilizing the power system is to bring the states back to their equilibrium values as fast as possible. This can be formulated as an optimization problem minimizing the cost index

$$J = \int_{t_0}^{t_f} dt \tag{A4}$$

where t_0 and t_f represent the initial and final values of transient duration under consideration. The optimal control problem can be restated as: given the second order non-linear system (A2) find u, which minimizes the cost function J of Eq. (A4) subject to constraint (A3), and brings the final angle to the stable manifold [0–π/2]. The final steady value of $\dot{\delta}(\Delta\omega)$ should be zero. Following the steps similar to that in Ref. [10], a quasi-optimum minimum-time control strategy can be expressed as

$$u = \begin{cases} 1 & \text{(braking resistor on) if } \Sigma \ge 0 \\ 0 & \text{(braking resistor off) if } \Sigma < 0 \end{cases} \tag{A5}$$

where

$$\Sigma = \gamma_1 \cup \gamma_2 \cup \gamma_3 \tag{A6}$$

$$\gamma_1 : \delta - \frac{\Delta\omega^2}{2[b\Delta P - b\,\mathrm{sgn}\{\Delta\omega\}]} = 0 \qquad \Delta\omega > 0$$

$$\gamma_2 : 0 \le \delta \le \pi/2$$

$$\gamma_3 : \delta - \frac{\Delta\omega^2}{2[b\Delta P - b\,\mathrm{sgn}\{\Delta\omega\}]} - \pi/2 = 0 \qquad \Delta\omega < 0$$

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