An adaptive PID stabilizer for power systems using fuzzy logic

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Abstract

A new gain scheduling PID stabilizer is designed for excitation control of power systems using fuzzy logic. The parameters of the proposed stabilizer are tuned on-line using a fuzzy rule base and a fuzzy inferencing mechanism for manipulating the speed error and its derivative. Although the new gain scheduled stabilizer does not have an apparent structure of PID controllers, fuzzy logic based controllers may be considered as nonlinear PID controllers, whose parameters can be determined on-line based on the error signal and their time derivative or difference. The new power system stabilizer is applied to single and multimachine power systems subject to various transient disturbances including faults. The superior performance of this stabilizer in comparison to the conventional fixed gain stabilizer proves the efficacy of this new approach.

Keywords: Fuzzy logic; PID stabilizer; Transient disturbances

1. Introduction

Many modern power systems comprise long transmission lines and remote sources of generation. Such systems have high series impedance which reduces system stability. Conventional stabilizers of fixed structure and constant parameters are tuned for one operating condition and can give optimal power system performance for that condition only. As the characteristics of power system elements are non-linear, the conventional stabilizers are not capable of providing optimal performance for all operating conditions [1–3].

Among the various control schemes proposed earlier, a supplementary excitation controller which can generate a damping signal in the excitation system has attracted widespread interest. Up to now, the lead-lag power system stabilizers have been widely used by power engineers. Other types of PSS such as proportional-integral PSS or proportional-derivative PSS [4] have also been proposed. The design of such stabilizers requires the specifications of proportional, integral and derivative gains and their adaptations with the changing operating conditions of the power system.

Variations of the controller parameters during changing operating conditions can be realized by different approaches. The fuzzy logic approach [5–9] offers the simplest way to relate the experience gained directly from the operation of the controlled power system to the value of the controller parameters with the changing system operation. If a conventional PI or PID control strategy is implemented by a microprocessor device, the fuzzy logic algorithm can be programmed by the same microprocessor device without any additional circuitry. Dedicated hardware could simplify the fuzzy logic implementation and reduce the computing time.

This paper presents a new design procedure for a simple fuzzy tuner for gain scheduling of a PI or PID power system stabilizer for different operating conditions of the power system. The parameters of the PID stabilizer span a prefixed range to avoid instability problems in the controlled power system. Satisfactory accuracy of the parameter adaptation is obtained by referring the fuzzy subsets to the normalized values of the variables involved in the fuzzy logic. The scaling factors are determined on-line by an appropriate procedure. This approach allows the values of PI or PD gains of the PSS to vary on-line during transient disturbances occurring on the system. Various simulations have been performed subject to several types of large

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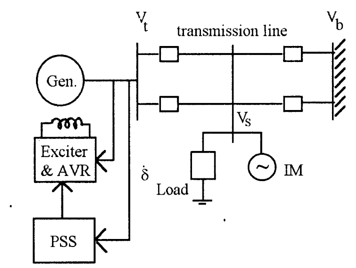
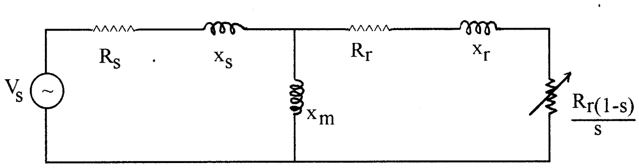
disturbances using a single-machine infinite-bus and a multimachine power system. Comparison studies have also been performed between a conventional proportional-integral power system stabilizer (CPSS) and fuzzy PI-PSS (or simply known as FPSS). The numerical simulation results clearly demonstrate the superiority of the PI gain scheduling fuzzy PSS in comparison to the CPSS.

2. Fuzzy gain scheduling of the PSS

Fig. 1 shows the model system used for non-linear simulation studies. The system comprises a single synchronous generator connected to a large power system through a double-circuit transmission line (Fig. 1a). In the simulations, a fifth order machine model is utilized. A simple first order induction motor model is used for simulation. To enhance system damping, the generator is equipped with a proportional-integral (PI) or proportional-integral-derivative (PID) PSS as shown in Fig. 2. The gain settings will be adapted by a fuzzy gain scheduler.



(a) Single machine infine-bus power system



(b) Induction motor model

Fig. 1. System model.

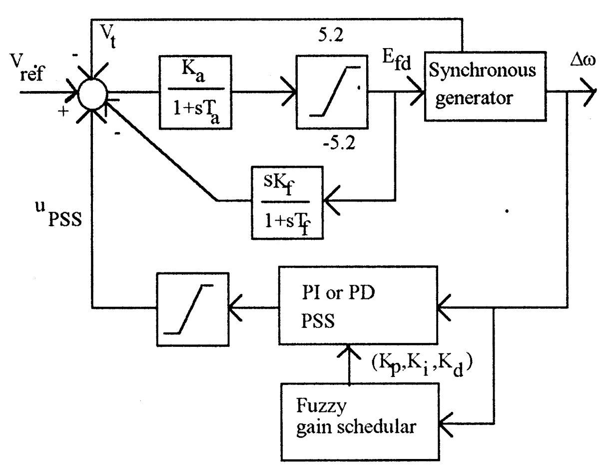


Fig. 2. Block diagram for the excitation system with a fuzzy gain scheduler.

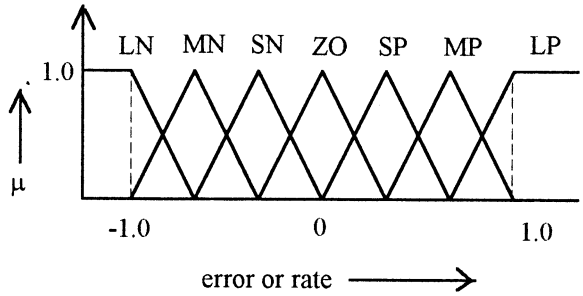


Fig. 3. Membership functions (sets) for error $\Delta\omega$ and its rate $\Delta\dot{\omega}$.

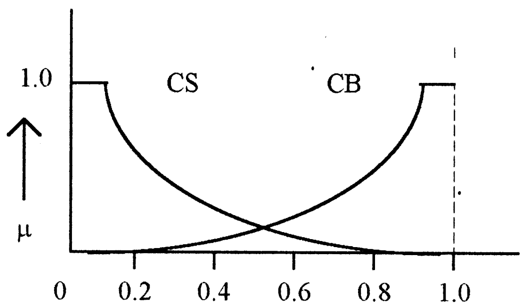


Fig. 4. Membership functions (sets) for C_p and C_d.

The approach used here exploits fuzzy rules and reasoning to generate controller parameters. It is assumed that K_p and K_d are in the prescribed ranges (K_{pmax}, K_{pmin}) and (K_{dmax}, K_{dmin}), respectively. The values of proportional and differential gains K_p and K_d are expressed as

$$K_p = (1 - C_p)K_{pmax} + C_p K_{pmin} \quad \text{and}$$
$$K_d = (1 - C_d)K_{dmax} + C_d K_{dmin} \tag{1}$$

where C_p and C_d are the coefficients for the min–max range of the proportional and derivative gains of the controller. The values of C_p and C_d are chosen here

$$0 < C_p < 1, \qquad 0 < C_d < 1 \tag{2}$$

The integral time constant is determined with respect to the derivative time constant as

$$T_i = \alpha T_d$$

In the Zeigler–Nichols PID tuning rule, the integral time constant T_i is taken as four times larger than the derivative time constant T_d ($\alpha = 0.25$). The integral gain is obtained as

$$K_i = \frac{K_p}{\alpha T_d}\,\alpha(K_p^2/K_d) \tag{3}$$

The parameters C_p, C_d and α in Eqs. (2) and (3), respectively, are determined by a set of fuzzy IF-THEN rules for the power system stabilizing signals like the machine speed deviation $\Delta\omega$ and its rate $\Delta\dot{\omega}$. However, instead of machine speed or its derivative, the change in the power output ΔP_e and its rate can be used as stabilizing signals to the PSS. The inputs to the fuzzy gain scheduler (Fig. 2) are

$$e(k) = \omega(k) - \omega_0$$

$$\dot{e}(k) = [e(k) - e(k-1)]/T \tag{4}$$

In Eq. (4), $e(k)$ and $\dot{e}(k)$ are the speed error and its rate at the kth sampling instant, and T is the sampling time period. We choose positive scaling factors g_e and g_r for the error and its rate so that

$$-1 \le g_e.e(k) \le 1, \qquad -1 \le g_r.\dot{e}(k) \le 1 \tag{5}$$

The constants g_e and $\cdot g_r$ are chosen to keep the maximum output of the fuzzy controller in the range $[-1, 1]$ at each sampling instant. Thus, $g_e = (1/e(\max))$, and $g_r = (1/\dot{e}(\max))$, the normalization of the error variable and its time derivative allows the number of fuzzy sets to be reduced without reducing the accuracy. Furthermore, in this way, the controlled plant becomes more sensitive to the control action when the error variable has a small amplitude. In computing the values of g_e and g_r, $e(\max)$ and $\dot{e}(\max)$ are the expected maximum error and maximum rate of change of error.

2.1. Fuzzification

The linear fuzzification algorithm for the scaled error and its rate are triangles, whose vertices are placed at -1, -0.666, -0.333, 0, 0.333, 0.666, 1 and are associated with fuzzy sets such as large negative (LN), medium negative (MN), small negative (SN), zero (ZO), small positive (SP), medium positive (MP), and large positive (LP). Similar sets are also used for the scaled rate of change of speed error. Fig. 3 shows the membership functions for $e(k)$ and $\dot{e}(k)$. For computing the parameters C_p and C_d, two fuzzy sets CB (C_p-big) and CS (C_p-small) are chosen and are characterized by the membership functions shown in Fig. 4, where the grade of the membership function μ is given by

$$\mu_{CB}(C_p) = -\frac{1}{a}\ln(C_p) \quad \text{and} \quad \mu_{CS}(C_p) = -\frac{1}{a}\ln(1 - C_p) \tag{6}$$

where the value of '$\dot{a}$' is chosen to get a suitable transient response. Similar equations hold good for the parameter C_d of the PID stabilizer. Furthermore the value of C_p or C_d is obtained from Eq. (6) as

$$C_p = \exp(-a\mu_{CB}(C_p)) \text{ for the set CB} \quad \text{and}$$
$$C_p = 1 - \exp(-a\mu_{CS}(C_p)) \text{ for the set CS.} \tag{7}$$

The choice of C_p or C_d in terms of the fuzzy sets big or small (B or S) can be explained in the following way:

When the dynamic system undergoes a transient change, the values of both the proportional gain K_p and integral gain K_i are to be kept large in comparison to derivative gain $K_d(K_{dmin})$. After the system settles to the steady state, the integral gain should be decreased to its minimum value, hence K_p has to be increased to its maximum value K_{pmax}.

Thus the variation of the proportional gain will be of the form

$$K_p = K_{pmax} - (K_{pmax} - K_{pmin})\exp(a - |error|) \tag{8}$$

If the error is large, $K_p = K_{pmax}$ and if the error is small $K_p = K_{pmin}$. From Eq. (8), it is evident that the value of 'a' controls the transient response, as K_p depends on it. The higher the value of 'a', then K_p reaches K_{pmax} faster and hence the transient overshoot is reduced faster. A suitable value of 'a', however, lies between 2 and 5.

To determine the integral gain, the value of a may be chosen from experience or may be considered as a fuzzy number which has a singleton membership function. The choice of a depends upon the requirement of a stronger integral action and in this study the value of a is varied between 0.2 and 0.5. A suitable value of 'a' is found as 0.4.

Table 1
The rule base for tuning C_p

$\dot{e}$ / e	LN	MN	SN	ZO	SP	MP	LP
LN	CB	CB	CB	CB	CB	CB	CB
MN	CS	CB	CB	CB	CB	CB	CS
SN	CS	CS	CB	CB	CB	CS	CS
ZO	CS	CS	CS	CB	CS	CS	CS
SP	CS	CS	CB	CB	CB	CS	CS
MP	CS	CB	CB	CB	CB	CB	CS
LP	CB	CB	CB	CB	CB	CB	CB

Table 2
The rule base for tuning C_d

$\dot{e}$ / e	LN	MN	SN	ZO	SP	MP	LP
LN	CS	CS	CS	CS	CS	CS	CS
MN	CB	CB	CS	CS	CS	CB	CB
SN	CB	CB	CB	CS	CB	CB	CB
ZO	CB	CB	CB	CB	CB	CB	CB
SP	CB	CB	CB	CS	CB	CB	CB
MP	CB	CB	CS	CS	CS	CB	CB
LP	CS	CS	CS	CS	CS	CS	CS

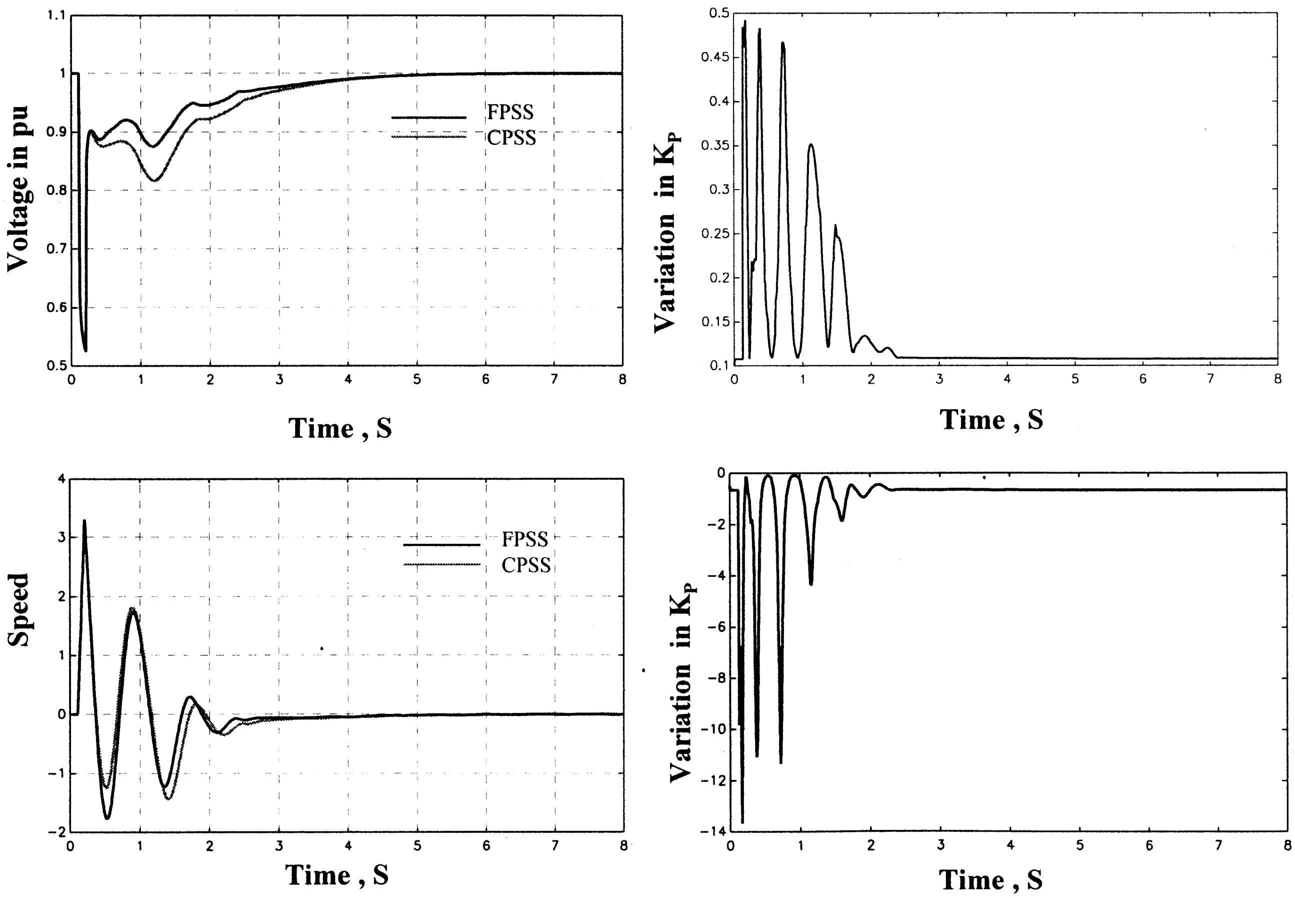


Fig. 5. Transient response to line to ground fault at $P = 0.8$ pu and $Q = 0.2$ pu.

2.2. Design of fuzzy rule base

Control rules are constructed based on the observations of the dynamic behaviour of the power system and switching curve. The rule base for tuning C_p consists of 49 rules and is shown in Table 1. In a similar way, Table 2 shows the rule base for tuning the parameter C_d.

2.3. Defuzzification stage

The final control output must be a discrete value indicating the switching states. A decision procedure must be employed in order to determine the parameter values C_p or C_d suggested by the membership values $\mu(C_p)$ or $\mu(C_d)$ defined in Eqs. (6) and (7).

Each fuzzy IF-THEN rule given in Tables 1 and 2 defines a fuzzy implication which is a fuzzy set obtained from the input–output product space. The rules are of the form:
Rule 1: If $e(k)$ is LN and $\dot{e}(k)$ is LN, then C_p is CB, C_d is CS and α is 0.5.

Here we use two commonly used fuzzy implication rules:
AND rule:

$$\mu_{CB}(C_p) = \min(\mu_E(e(k)), \mu_R(\dot{e}(k))) \quad (9)$$

OR rule:
and for the OR operation

$$\mu_{CS}(C_p) = \min(1, \mu_E(e(k)) + \mu_R(\dot{e}(k)))$$

where $\mu_E(e(k))$ and $\mu_R(\dot{e}(k))$ denote the grade of membership of the error $e(k)$ and its rate $\dot{e}(k)$ in the error set E, and rate set R, respectively.

The defuzzified output C_p or C_d is calculated using a centroid defuzzification rule as

$$C_p = [\mu_{CB}(C_p).\exp(-a\mu_{CB}(C_p)) + \mu_{CS}(C_p) (1 - \exp(-a\mu_{CS}(C_p))/\sum(\mu_{CB}(C_p) + \mu_{CS}(C_p)) \quad (10)$$

In a similar way, the value of C_d can be found out.

$$C_d = [\mu_{CB}(C_d).\exp(-a_1\mu_{CB}(C_d)) + \mu_{CS}(C_d) (1 - \exp(-a_1\mu_{CS}(C_d))/\sum(\mu_{CB}(C_d) + \mu_{CS}(C_d))$$

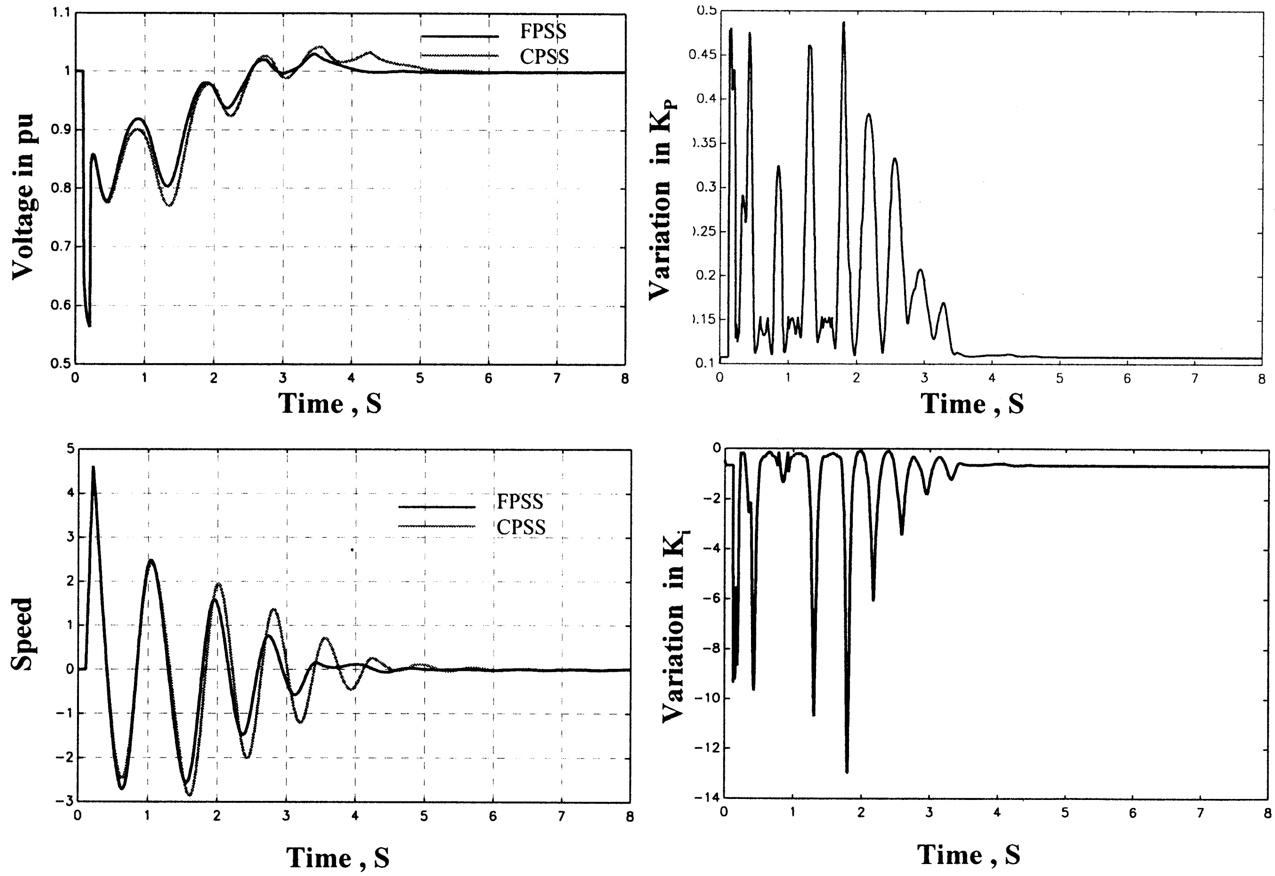


Fig. 6. Transient response of line to ground fault at $P = 1.1$ pu, $Q = 0.4$ pu.

The values of a and a_1 are obtained for this simulation as $a = 2.5$ and $a_1 = 2$.

3. System studied

3.1. System 1: a single machine connected to an infinite busbar

The conventional proportional–integral power system stabilizer has the following transfer function:

$$u_{\mathrm{PSS}} = \left(K_{\mathrm{p}} + \frac{K_{\mathrm{i}}}{s}\right)\left(\frac{sT_Q}{1 + sT_Q}\right)$$

The data for the generator and excitation system are obtained as

$$x_d = 1.99, \quad x'_d = 0.3, \quad x''_d = 0.21, \quad x_q = 1.87, \quad x'_q = 0.45, \quad x''_q = 0.21, \quad T'_{do} = 5.4, \quad T''_{do} = 0.053, \quad T'_{qo} = 1.33, \quad T''_{qo} = 0.061, \quad x_t = 0.4, \quad H = 3.5, \quad K_a = 50, \quad T_a = 0.03, \quad K_f = 0.022, \quad T_f = 1.0, \quad T_Q = 2.5.$$

The operating conditions are:

$$P = 1.1, \quad Q = 0.4, \quad P_L = 0.3, \quad Q_L = 0.1, \quad a_p = 1.5, \quad a_q = 3.5$$

The induction motor parameters are:

$$x_m = 4.016, \quad x_s = 0.11, \quad x_r = 0.0866, \quad R_s = 0.004, \quad R_r = 0.004 \text{ and slip} = 0.05$$

All reactances are in pu and time-constants in s.

The values of proportional gain K_{p} and integral gain K_{i} for the CPSS are chosen for this system as $K_{\mathrm{p}} = 0.1$, $K_{\mathrm{i}} = -0.5$. For the fuzzy logic based stabilizer, the values of the proportional and integral and derivative gain limits are chosen as

$$K_{\mathrm{pmax}} = 0.5, \quad K_{\mathrm{pmin}} = 0.1, \quad K_{\mathrm{dmax}} = 0.05, \quad K_{\mathrm{dmin}} = 0.005$$

The parameters of the CPSS are kept unchanged for the following tests in the several transient stability simulations of the sample power system shown in the paper. A higher value of K_{p} ($K_{\mathrm{p}} = 0.2$) for the CPSS yielded poorer results. The scaling factor g_{e} and g_{r}, for the FPSS are $g_{\mathrm{e}} = 0.2$ and $g_{\mathrm{r}} = 0.02$.

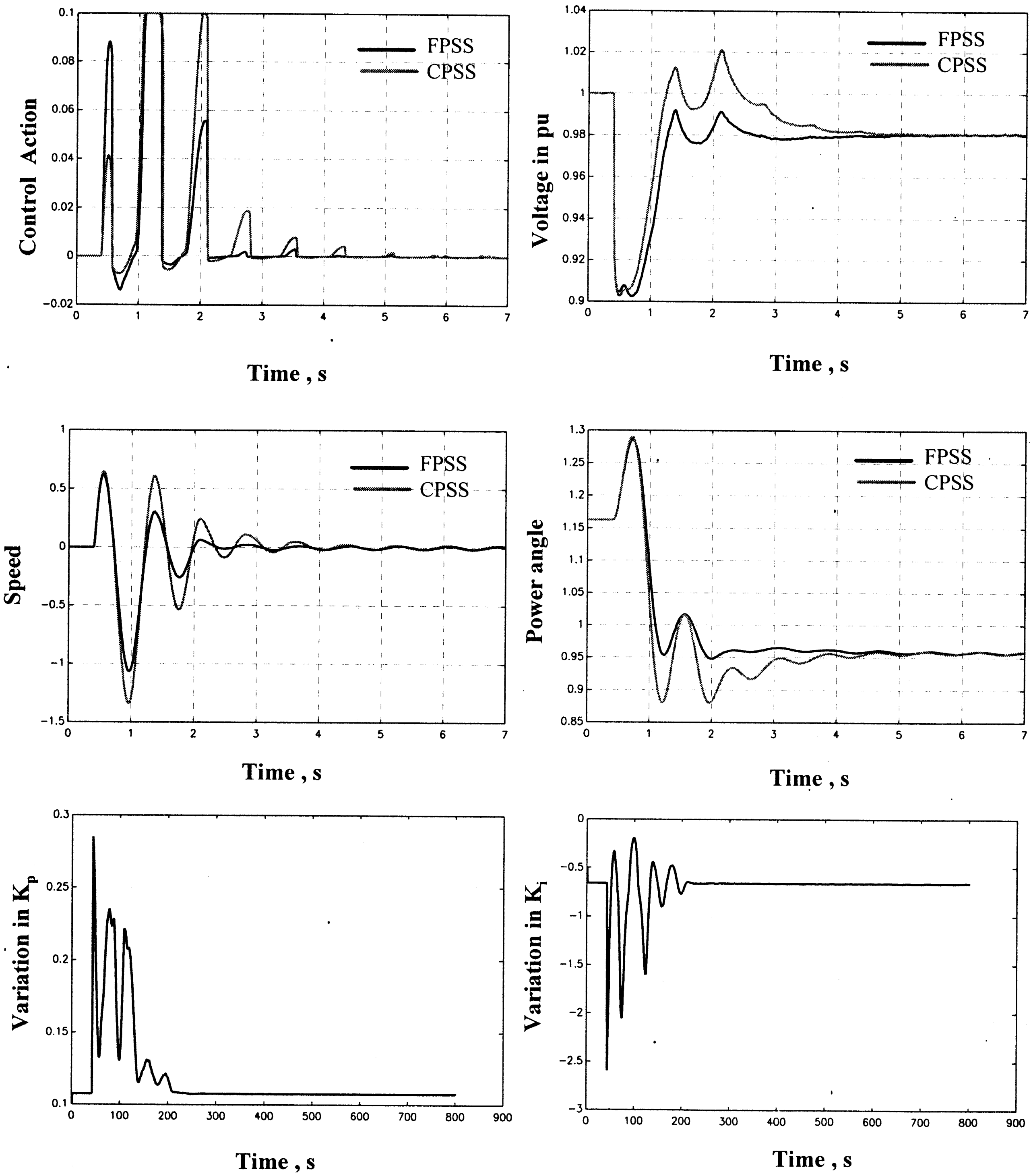


Fig. 7. Transient response to random variation of infinite bus voltage followed by a 20% dip in magnitude.

3.1.1. Fault test

To verify the behaviour of the proposed fuzzy PI-PSS under large signal disturbance conditions, a 3-phase fault is applied at the infinite bus (with active and reactive power P and Q fixed at $P = 0.8$, $Q = 0.2$) and cleared after 100 ms. The gains of the CPSS are tuned to provide an optimized response in this case. The response is shown in Fig. 5. It can be seen from the figure that the fuzzy logic based PSS (FPSS) and conventional fixed gain PSS (CPSS) produces almost equal damping to the oscillations in speed and terminal voltage of the machine.

The active and reactive power outputs of the generator are then increased to $P = 1.1$, $Q = 0.4$, respectively,

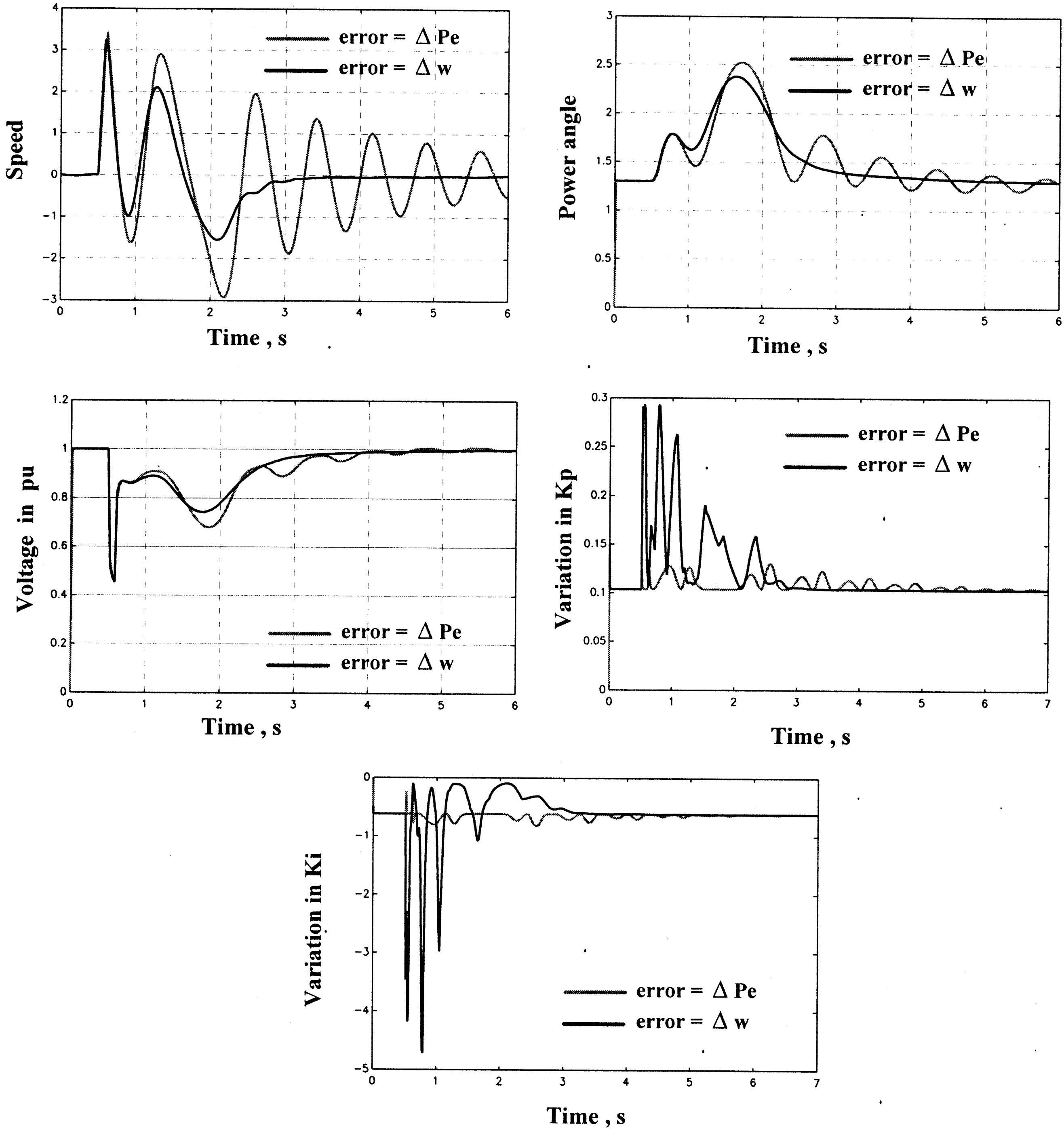


Fig. 8. Comparison of transient response to a single line to ground fault ($P = 0.8$ pu, $Q = -0.1$ pu).

and the response for the same 3-phase fault is shown in Fig. 6. In this case the response with fixed gain CPSS control is found to be oscillatory and the system control takes a longer time to stabilize. However, with the adaptive fuzzy logic based PSS, the transient response of the system improves significantly and the oscillations in the machine speed are damped out very quickly.

The voltage of the infinite bus is then reduced by 20% suddenly and a random variation of 10% of the bus voltage is superimposed. The random variation of the bus voltage is generated using a pseudo-random sequence. The performance of both the CPSS and FPSS is shown in Fig. 7 for damping the electro-mechanical oscillations due to the sudden change in infinite bus voltage. From the figure it is observed that the FPSS produces better damping performance in comparison to the conventional CPSS. The variations of K_p and K_i are also presented in this figure. The figure also reveals the

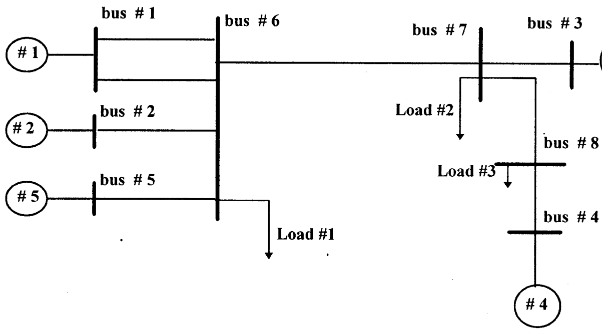


Fig. 9. A five-machine power system.

random variations of the terminal voltage of the generator due to random voltage fluctuations at the infinite bus.

Instead of using the speed deviation signal for deriving the K_p and K_i for the fuzzy logic based PSS, the active power deviation (ΔP_e) can also be used for power system stabilization. The comparison between the transient response of the generator to a single-line to ground fault using either ΔP_e or $\Delta\omega$ as the error signal is shown in Fig. 8. From the figure it is evident that the speed deviation signal is more potent in stabilizing electromechanical oscillations of the power system. Significant damping is provided by the $\Delta\omega$ signal.

3.2. System II: a multimachine system

A five-machine power system without infinite bus, as shown in Fig. 9 is used to test the proposed fuzzy logic based adaptive PI controller. Parameters for all the generating units, transmission lines and loads, and operating conditions are given in Appendix A. This system is found to have a local mode of oscillation of about 1.3 Hz and inter-area mode of about 0.65 Hz without any PSS installed. The speed deviations between generator 1 and 2 exhibit mainly local mode oscillations while generators between 2 and 3 exhibit mainly inter-area oscillations.

3.2.1. Fault test

To damp both the local and inter-area modes of oscillation, CPSS is installed on generators 1, 2, and 3. A 3-phase to ground fault is applied at the middle point of one transmission line between buses 3 and 6 and the fault duration is 100 ms. The response of the system under this disturbance with CPSS and fuzzy logic based adaptive PI-PSS (FPSS) is shown in Fig. 10. It can be seen from the figure that the performance of the FPSS is significantly greater than CPSS in damping out both inter-area and local mode oscillations.

For the same operating conditions and the application of the 3-phase to ground fault, the performance of the system with CPSS installed on all the generators is shown in Fig. 11. The figure also presents the performance with FPSS on all the generators which shows a remarkable improvement in system performance. The oscillations and transient overshoots are significantly reduced for all the generators.

4. Conclusions

A new tuning algorithm for PI or PID stabilizers, using fuzzy logic, for power systems is presented in this paper. The adaptive proportional integral or proportional-derivative controllers, whose gains are adjusted on-line based on the speed error signal and its derivative, can offer better damping effects for generator oscillations over a wide range of operating conditions than conventional PI or PID controllers with fixed gain settings. Numerical simulation results for a single-machine infinite bus and multimachine power system prove the efficacy of the tuning procedure of the PI or PID stabilizers.

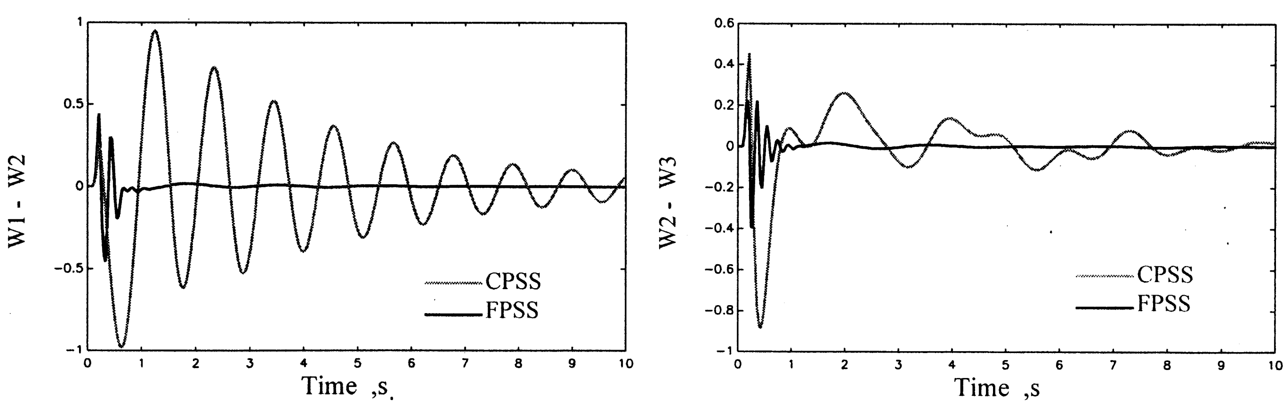
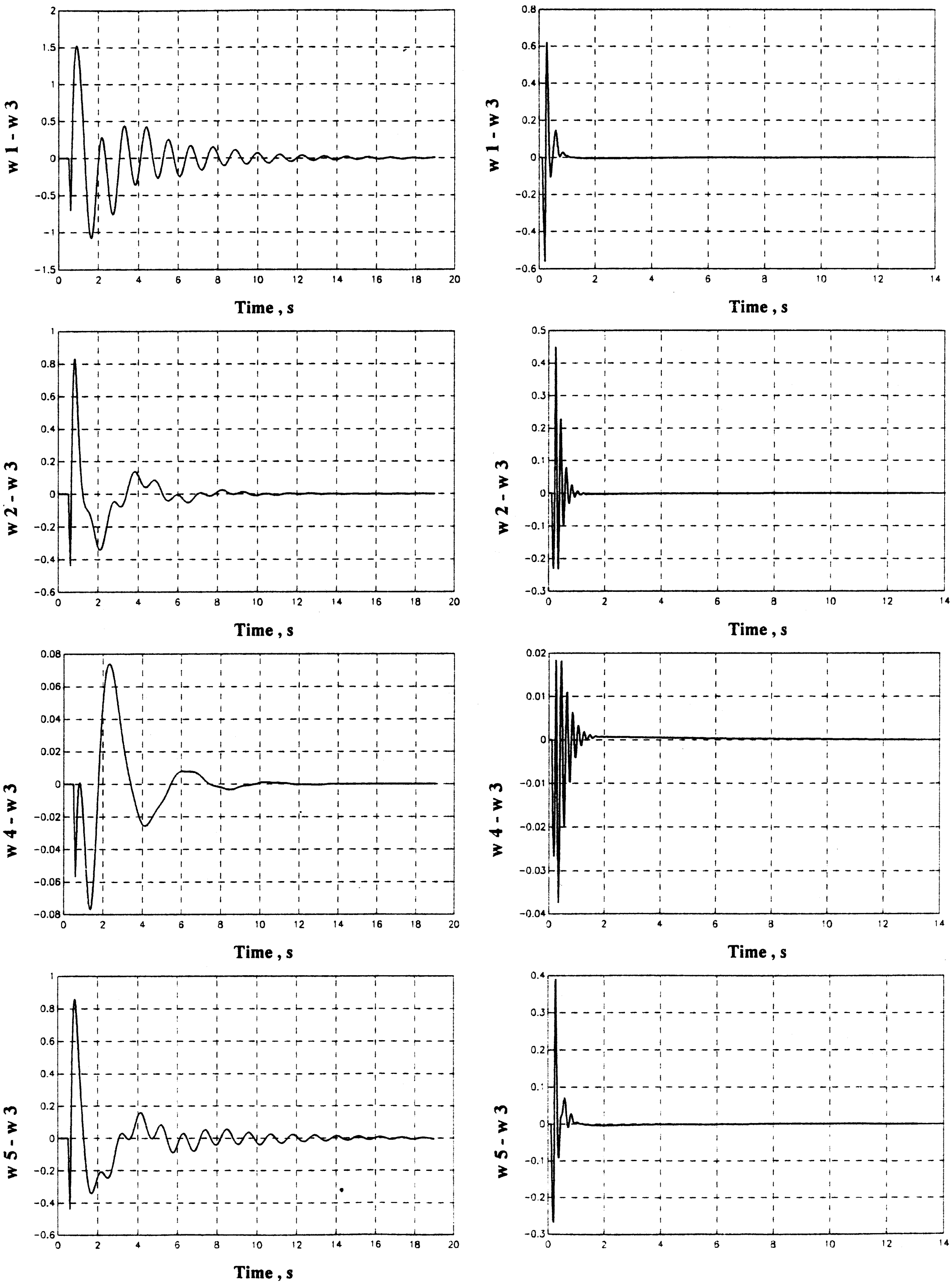


Fig. 10. Transient response for a 3-phase to ground fault.



(a) Performance with CPSS applied to all machines

(b) Performance with Fuzzy Controller applied to all machines

Fig. 11. Transient response to a 3-phase to ground fault.

Appendix A

The generating unit is modelled by five first-order differential equations given below

$$\dot{\delta} = \omega - \omega_0$$

$$\dot{\omega} = \frac{\pi f}{H}(T_{\mathrm{m}} - T_{\mathrm{e}})$$

$$T'_{d0}\dot{e}'_q = e_f - (x_d - x'_d)i_d - e'_q$$

$$T''_{d0}\dot{e}''_q = [e'_q - (x'_d - x''_d)i_d - e''_q] + T''_{d0}\dot{e}'_q$$

$$T''_{q0}\dot{e}''_d = -(x_q - x''_q)i_q - e''_d$$

Where T_{e} is electric torque output of the generator. The CPSS has the following structure:

For a multimachine power system, the CPSS structure is given by

$$K_s \cdot \frac{sT_Q}{1 + sT_Q}\left(\frac{1 + sT_1}{1 + sT_2}\right)$$

where

$$K_s = 0.1, \quad T_Q = 2.5, \quad T_1 = 0.3, \quad T_2 = 0.04.$$

Parameters of the generators

	Generator 1	Generator 2	Generator 3	Generator 4.	Generator 5
x_d	0.0260	0.1026	0.1026	0.1026	0.0260
x_q	0.6580	0.0658	0.0658	0.0658	0.6580
x'_d	0.3390	0.0339	0.0339	0.0339	0.3390
x''_d	0.2690	0.0269	0.0269	0.0269	0.2690
x''_q	0.3360	0.0335	0.0335	0.0335	0.3360
T'_{d0}	5.6700	5.6700	5.6700	5.6700	5.6700
T''_{d0}	0.6140	0.6140	0.6140	0.6140	0.6140
T''_{q0}	0.7230	0.7230	0.7230	0.7230	0.7230
H	10.000	80.000	80.000	80.000	10.000

Parameters of AVRs and simplified ST1A exciters

	Generator 1	Generator 2	Generator 3	Generator 4	Generator 5
T_R	0.0400	0.0400	0.0400	0.0400	0.0400
K_A	190.00	190.00	190.00	190.00	190.00
K_c	0.0800	0.0800	0.0800	0.0800	0.0800
T_B	10.000	10.000	10.000	10.000	10.000
T_C	1.0000	1.0000	1.0000	1.0000	1.0000

Parameters of transmission lines in pu

Bus No.	R	X	$B/2$	Bus No.	R	X	$B/2$
1–7	0.00435	0.01067	0.01536	2–6	0.00213	0.00468	0.00404
3–6	0.01002	0.03122	0.03204	3–6	0.01002	0.03112	0.03204
4–8	0.00524	0.01184	0.01756	5–6	0.00711	0.02331	0.02732
6–7	0.04032	0.12785	0.15858	7–8	0.01724	0.04153	0.06014

Operating conditions and loads for all tests:

	Generator 1	Generator 2	Generator 3	Generator 4	Generator 5
P (pu)	5.1076	8.5835	0.8055	8.5670	0.8501
Q (pu)	6.8019	4.3836	0.4353	4.6686	0.2264
V (pu)	1.0750	1.0500	1.0250	1.0750	1.0250
δ (pu)	0.0000	0.3167	0.2975	0.1174	0.3051

Load in admittances in pu

$$L_1 = 7.5 - j5.0 \quad L_2 = 8.5 - j5.0 \quad L_3 = 7.0 - j4.5$$

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