CHAPTER 8

STABILITY ENHANCEMENT OF A MULTIMACHINE POWER SYSTEM USING AN ANN-FL PSS

In a stable power system, all the synchronous generators operate in synchronism. When perturbed, they must either return to their original state if no net change of power occurs or reach a new state asymptotically without losing synchronism. It is difficult to theoretically prove whether a multimachine power system is stable. The objective of this chapter is to show how power system stability can be further enhanced by using an ANN–FL power system stabilizer(PSS). Two power system stabilizers based on the ANN–FL modelling technique, one using speed deviation as input and the other using accelerating power, are designed and applied to a two–machine infinite–bus system to evaluate their performance.

8.1 INTRODUCTION

To meet a steady demand growth of interconnected power systems, the size of generating units has been increased, and high–speed excitation systems have been introduced. By doing so negative damping to the interconnected system is resulted, causing low–frequency oscillations. Weak line transmissions are another contributing factor to these oscillations. Nevertheless, electro–mechanical oscillations of low frequency become inherent characteristics of power systems. The presence of such oscillations has been reported worldwide[8–1]~[8–5]. Low frequency oscillations are also called system modes. Principally, there are two categories of modes: inter–area modes associated with one group of generators or plants at one end of a tie–line oscillating against another group at the other end and local modes associated with weakly connected power systems or remote generating units weakly connected to a large power system. Different system modes can occur simultaneously. This coupling among modes makes it difficult to define 'cause and effect' relationships in analysing the dynamic behaviour of a multi–machine system, especially for inter–tie line oscillations [8–6]~[8–9]. Eigenvalue analysis is a fundamental technique to study the nature of system modes of a power system [8–10,8–11]. A positive real part of a swing mode indicates a negatively damped mode which needs controlling to ensure stable system operation. This technique is also used in this thesis in designing the conventional PSSs for the generators.

The common remedy for inadequate damping is to utilize additional excitation control by means of power system stabilizers [8–7,8–12]. After more than two decades of research and practical applications, PSSs are now in wide use in power systems. In most PSS applications, only local feedback control is used. Multivariable and optimal stabilizers can also be theoretically designed but may not be implemented because of the difficulties in accessing most of the feedback variables. Coordination in PSS design has been taken into account by either eigenanalysis [8–13], or frequency domain methods [8–14] or a hybrid of the two [8–15]. No matter what algorithm is employed in tuning the settings of a PSS, the more information dependent on operating conditions is used, the less robust the PSS will be to system changes.

In [8–5], a simple PSS design procedure is proposed and used in a practical power system of longitudinal structure. Usually, system modes must be known in PSS design. It is also generally true that the damping (real part) of a system mode is more sensitive to operating conditions than the frequency (imaginary part) of that mode. Reduction of these sensitivities of a mode increases the robustness of the PSS designed based on this mode. Instead of using a specific frequency for a particular PSS design, an average frequency is derived for each coherent group of generators that oscillate together. The coherent generation groups can be identified by available methods [8–16,8–17]. Another parameter needed in tuning a PSS is a lead/lag time constant spread [8–7,8–8]. Nonlinear simulation is utilized to determine the optimum gain of each PSS. Input signals to all the PSSs in each coherent generation group may be communicated with each other among the strongly coupled generators. The total coupling factors [8–18] computed from eigenanalysis can be employed to take into account these interactions among generators. The design procedure developed in this paper was successfully used in another research project leading to the publication of [8–19]. This procedure will be used in this thesis to design benchmark PSSs for training ANN–FL power system stabilizers.

Though, there have been many examples of successful applications of conventional PSSs, difficulties include the tuning of a PSS for a wide range of operating conditions, as well improving the performance under different contingencies. PSSs that utilize shaft speed as input signal may result in torsional oscillations. PSSs using power signals may cause voltage fluctuations. In recent years, alternative control strategies have been investigated, especially intelligent control. Chapter 1 has reviewed a few intelligent control schemes based on artificial neural networks(ANNs) and fuzzy logic control(FLC). In this category of applications, publications [8–20]~[8–25] are closely related to the subject of this chapter. The theme of those papers is to develop an event driven controller representing a nonlinear mapping from the input to the output variables. Fuzzy logic control is a structured representation technique, it does not allow learning nor adaptation. On the other hand, artificial neural networks are unstructured numerical estimators that can learn, generalize and process massive sensory information. An intelligent controller designed on the basis of the hybrid theory of ANN and FL presented in Chapter 4 combines the merits of both modelling techniques.

8.2 STABILITY ANALYSIS

8.2.1 A Multimachine Power System

A single–line diagram of the multimachine power system used in the simulation studies is shown in Figure 8.1. The system consists of two hydro generators, one load, and one infinite bus. Generator #1 is a test machine, modeled by a fifth–order model with subtransient (GEN_4)(see Appendix D), simulating a single generator in the system. Generator #2 is an equivalent machine modeling a local power system. It is simulated by a fifth–order model with transient (GEN_3). The infinite bus (GEN_0) is the connecting point with a remote power system. Each machine is equipped with a simple static (SCR) excitation system (ST_4) and a standard hydro speed–governing and turbine system (GOV_221). Figure 8.1 shows the parameters of the network. Parameter values for the various power devices are listed in Tables C.1–C.3.

Two load flow studies were carried out using the decoupled fast load flow program(Chapter 7). Tables 8.1–8.2 list the obtained results, including voltage magnitude and angle, injected real and reactive power, power flow in each transmission line and power losses. The operating point of Case A will be used for conducting eigenanalysis and later on for designing conventional power system stabilizers(CPSSs). The operating point of Case B is designed for performance evaluation.

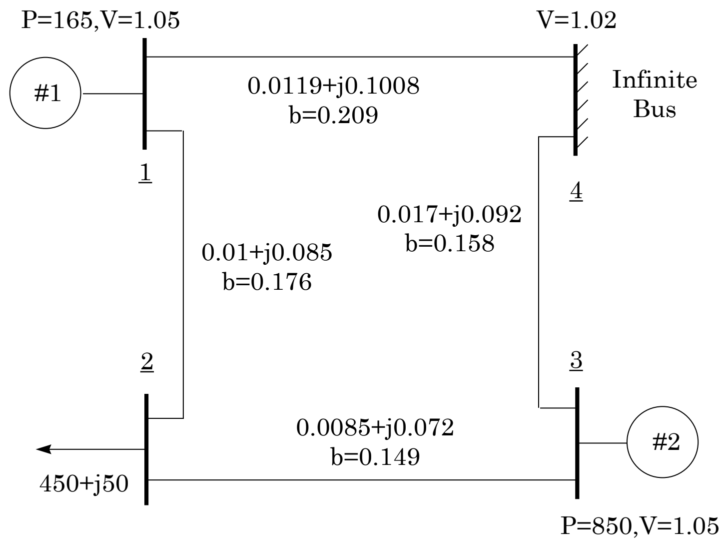

Fig. 8.1 Single–Line Diagram of the Two Machine Infinite Bus System

8.2.2 Stability Studies

(1) *Steady–State Stability*

In an interconnected power system, there are hundreds of oscillatory modes. Usually two distinct types of system oscillations, as has been outlined in the previous section, are recognized in an analysis of system stability and control problem. They are referred to as local plant modes and inter–area modes. The fundamental objective of excitation control is to provide maximum damping to both types of modes, and at the same time to enhance transient stability.

Part of this objective is accomplished by using supplementary excitation control through a conventional power system stabilizer(CPSS). For the purpose of designing a CPSS, an eigenanalysis was conducted for the study system. Two oscillatory modes were calculated. The local mode of the test machine is $1.6928\,Hz$ and the inter–area mode is $0.7813\,Hz$. Based on the design procedure presented in [8–4], two CPSSs were designed and tuned, one for the test machine, and the other for the equivalent machine. They will be used in the performance studies later in this chapter. A study of the system's frequency response was also performed. The response was obtained by simulating the study system in TSSP in SIMULINK environment. The disturbance to the system is a three–phase to ground fault for 6–cycles applied to the terminal bus of generator #1. The speed change of the generator was measured, and sampled at a sampling rate of $66.67\,Hz$.

A 512–point fast Fourier transform(FFT) was applied to the sampled data sequence, and the power spectral density, a measurement of the energy at various frequencies, was calculated. Figure 8.2 shows the semi–logarithmic plot of the power spectral density. It can be seen that the two oscillatory modes are approximately $0.8\,Hz$ and $1.70\,Hz$. This is in agreement with what has been calculated from eigenanalysis.

(2) *Transient Stability*

In the studies reported in this section, a three–phase to ground fault for 6–cycles was applied on the line between buses #1 and #2 near the terminal bus of generator #1. The simulation model is given by Fig. 8.3, using TSSP under SIMULINK. In view of the large number of variables and study cases involved, only the excitation voltage and rotor angle responses are shown in Figs. 8.4 and 8.5. The results of the transient simulations show that:

- For the case of CPSS with TGR, the inter–area mode oscillation is much pronounced (curve #4 of Fig. 8.5). The output of the exciter hits its upper limit only at the first swing(curve#4 of Fig. 8.4(b)). The overall performance of the excitation plus CPSS system can be improved by increasing the CPSS gain[8–24];
- For the case of CPSS without TGR, the excitation plus CPSS system improves damping and transient stability on both oscillatory modes(curve #3 of Fig. 8.5). The exciter reaches its ceiling voltages during the first two swings to provide maximum control action(curve #3 of Fig. 8.4(b));
- For the case of no CPSS, with TGR, the rotor angle oscillation is more damped and transient response is improved(curve #2 of Figs. 8.5 and 8.4(a)), as compared with the case of no TGR. This is true for local mode only. Its effect on the inter–area mode is imposed on to the local mode oscillation.
- For the case of no PSS and no TGR, the system is highly oscillatory. This scenario will be used to test whether a PSS can stabilize the system.

Table 8.1 Load Flow Results: Node Power(MW+jMVar)

Case	Bus #	V (pu)	θ (deg)	Generation	Load
A	1	1.050	6.4265	165+j69	––
	2	0.992	4.7698	––	450+j50
	3	1.050	21.2538	850+j111	––
	4	1.020	0.0	-519.9+j91.2	––
B	1	0.977	-8.9523	125+j50	
	2	0.910	-23.9549	––	750+j50
	3	1.050	-2.9906	450+j261.1	––
	4	1.050	0.0	211.3-j23.75	––

Table 8.2 Load Flow Results: Branch Power(MW+jMVar)

Case	Line $i-j$	S_{ij}	S_{ji}	Losses
A	1–2	43.29+j57.10	-42.72-j70.58	0.58-j13.48
	2–3	-407.28+j20.58	421.67+j85.75	14.39+j106.34
	3–4	428+j25.56	-399.86+j111.6	28.47+j137.15
	1–4	121.7+j12	-120-j20.38	1.66-j8.34
B	1–2	180+j71	-271-j11.4	8.89+j59.9
	2–3	-478-j38.6	502+j224	23.6+j185.7
	3–4	-52+j36.78	53-j49.7	0.74-j12.9

	1–4	-155-j21.24	158+25.9	3.02+4.71

Fig. 8.2 Frequency Response Showing the Two Oscillatory Modes

Fig. 8.3 Simulation Model of the Study System

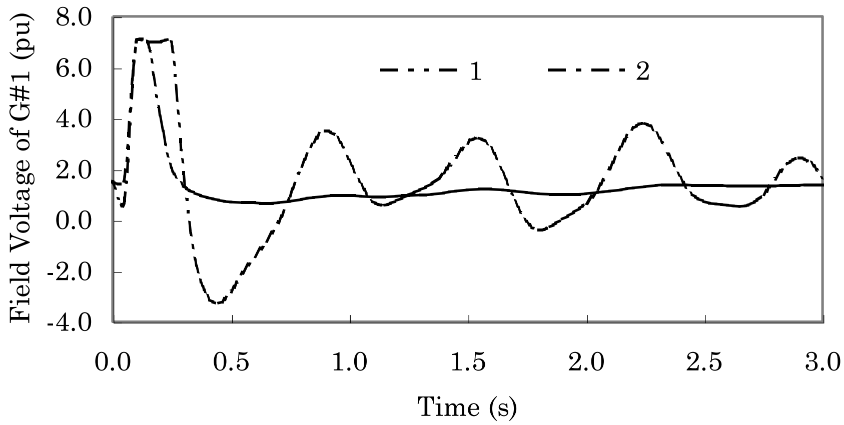

Fig. 8.4(a) Field Voltage Responses of the Test Machine, Following A 3–Phase To Ground Fault of 6–Cycles at the Terminal Bus of G#1

Curve #1 —No Transient Gain on AVR, No CPSS

Curve #2 —With Transient Gain on AVR, No CPSS

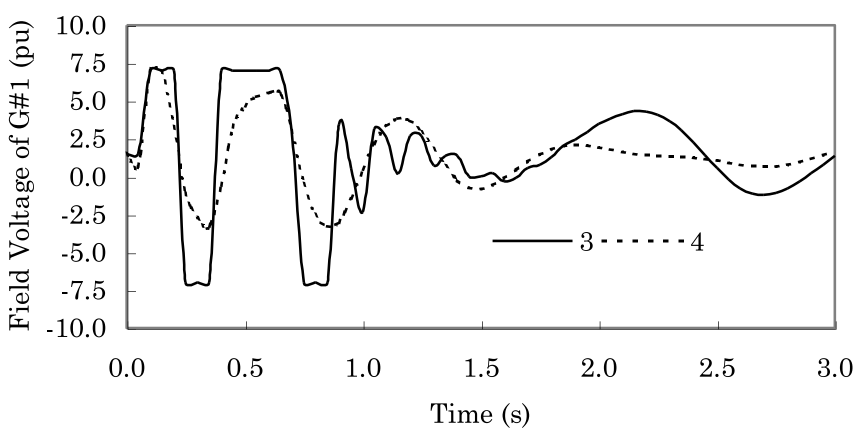

Fig. 8.4(b) Field Voltage Responses of the Test Machine, Following A 3–Phase To Ground Fault of 6–Cycles at the Terminal Bus of G#1

Curve #3 —No Transient Gain on AVR, with CPSS

Curve #4 —With Transient Gain on AVR and CPSS

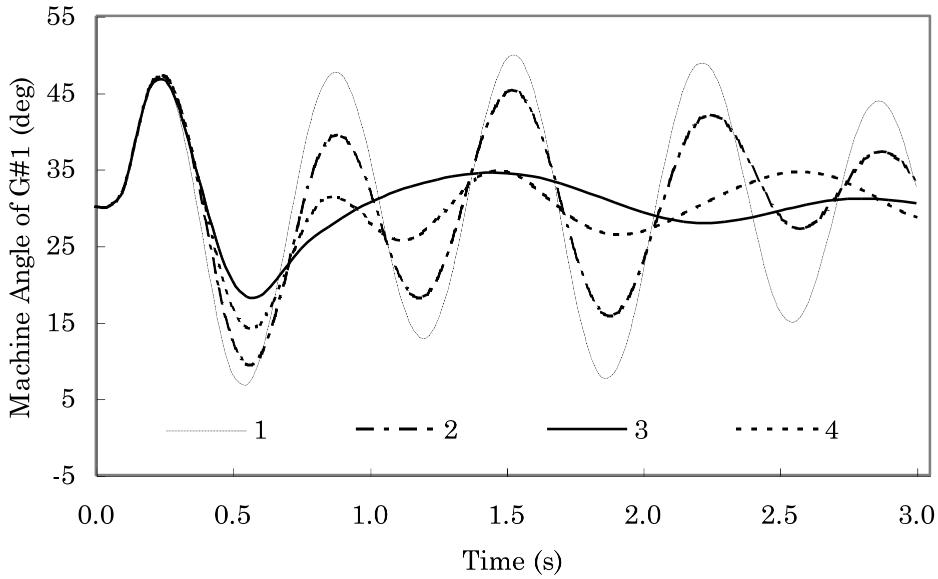

Fig. 8.5 Generator Angle Responses of the Test Machine, Following A 3–Phase To Ground Fault of 6–Cycles at the Terminal Bus of G#1 (Curve No. and description agree with those of Figs. 8.4(a) & (b))

8.3 DESIGN OF TWO ANN-FL PSSs

8.3.1 General Comments

The most difficult problem that a designer tries to solve is to make the best compromise in choosing PSS parameter values so that the controller will yield best performance when it faces environmental changes. Such a goal may never be truly realized in practice as the design is purely based on linear control theory where such a designed controller operates at its optimum only at the environment for which it is designed.

An hybrid of artificial neural network and fuzzy logic power system stabilizer(ANN–FL PSS) is a trained fuzzy logic controller. It combines the merits of both neural networks and fuzzy logic to form an intelligent control system. In this section, two ANN–FL power system stabilizers are designed, one using speed deviation of the generator as the input signal, the other using accelerating power.

The design procedure employed is similar to that used in Chapter 5, though, there are specific concerns in each design. The two controllers to be designed will have the same structure as that used in Chapter 5. The training program is similar to that of Chapter 5, with only minor modifications. The emphasis of this chapter will be focused on the performance of the two ANN–FL PSSs, when they are applied to a multimachine power system. Six aspects of information are needed to design an hybrid ANN–FL control scheme. They are outlined in the next section.

8.3.2 ANN–FL PSS Using Speed Deviation

(1) *Linguistic Variables*

As the objective of a power system stabilizer applied to a synchronous generator control is to damp rotor oscillations, it is natural to monitor the speed and to use it as a feedback control variable. Since speed deviation is a result of the unbalanced torque applied to the rotor shaft, the key to bringing the speed deviation to zero is to reduce the unbalanced torque to zero. This residual torque equals the summation of the positive mechanical input torque from the prime mover and the negative electrical torque output from the generator. For the first few seconds after a system disturbance, due to technical reasons, the mechanical torque can not be changed dramatically to bring the residual torque to zero. It is the electrical torque that must be changed. The electrical torque is directly proportional to the excitation voltage and inversely proportional to the speed of the machine. Therefore, the excitation voltage could be chosen as the output variable of the controller to be designed. Only there is another problem; the excitation voltage is also controlled by a voltage regulator. The function of this control loop is to manage the reactive power flow in the system so that a desired voltage profile can be maintained during steady–state operations of the system.

To maintain the functionalities of the excitation system for both steady–state and transient operations, the control signal from the stabilizing controller can be introduced to the low signal front end of the excitation system as supplementary control. During steady–state operation, this supplementary signal must be zero. During transient operations, it must be able to control the excitation voltage to act according to the change of the speed. Another input variable to the controller can be the rate of speed change, as has been used in Chapter 5. Therefore, the two fuzzy inputs and one fuzzy output variables can be expressed as:

$$\Delta\omega = [NB, NM, NS, PS, PM, PB] \tag{8.1}$$

$$\Delta\omega / \Delta t = [NB, NM, NS, PS, PM, PB] \tag{8.2}$$

$$\Delta V = [N, P] \tag{8.3}$$

where the various linguistic labels are defined as negative big(*NB*), negative medium(*NM*), negative small(*NS*), positive small(*PS*), positive medium(*PM*), positive big(*PB*), negative(*N*), and positive(*P*).

(2) *Membership Functions*

By expert's knowledge, the ranges of change of these fuzzy variables defined above is known. Therefore, the universe of discourse of the fuzzy sets can be determined as follows:

$$\Delta\omega = [-0.1, +0.1]\,(pu) \tag{8.4}$$

$$\Delta\omega / \Delta t = [-10, +10]\,(pu/s) \tag{8.5}$$

$$\Delta V_s = [-0.4, +0.4]\,(pu) \tag{8.6}$$

Six membership functions are assigned to each of the two input fuzzy variables, and two membership functions assigned to the output variable. The structure of the membership functions of the state variables $\Delta\omega / \Delta t, \Delta\omega$, and ΔV_s are the same as shown in Figs. 5.5 – 5.7, only the universes of discourse are different. Membership functions for fuzzy sets $A_{i2}, \ldots, A_{i5} (i = 1,2)$ are expressed by triangular functions which take the form of (8.7), shown in Fig. 8.6, and membership functions for fuzzy sets $A_{i1}, A_{i6}, B_i (i = 1,2)$ are expressed by trapezoidal functions which take the form of (8.8), shown in Fig. 8.7. Table 5.1 lists eighteen rules used as the rule base in designing the ANN–FL power system stabilizers.

$$f(x,a,b,c)=\begin{cases}\dfrac{x-a}{c-a}, & a\le x\le c,\\[2mm] \dfrac{b-x}{b-c}, & c\le x\le b,\\[2mm] 0, & otherwise.\end{cases} \tag{8.7}$$

$$f(x,a,b,c,d)=\begin{cases}\dfrac{x-a}{b-a}, & a\le x\le b,\\[2mm] 1, & b\le x\le c,\\[2mm] \dfrac{d-x}{d-c}, & c\le x\le d,\\[2mm] 0, & otherwise.\end{cases} \tag{8.8}$$

(3) *Data Collection and Training*

A number of simulation studies were carried out on the two–machine power system, using both the speed power system stabilizer(PSS) and the accelerating power PSS similar to those of [8–19]. The disturbances used in the studies were (a) a three–phase to ground fault at the terminal bus of generator #1 for 6 cycles; (b) a step reference voltage change of +4% to the automatic voltage regulator(AVR). The load level was changed to 100%, 75%, and 50%, respectively, when the three–phase fault was applied to the system. Each simulation lasted three seconds. The obtained time–domain responses were sampled with a sampling frequency of 100 Hz. The sampled results were saved in text files as listed in Table 8.3 for compiling training and checking data sets.

(4) *Display of the Trained ANN–FL PSS*

A structure of five–layer feedforward network similar to that of Fig. 5.8 is used as the ANN–FL PSS controller. The universe of discourse of each input variable is initially divided into six segments. Each segment is assigned a membership function with initial parameters. This five–layer feedforward network was then trained using the collected data set and checked. Figures 8.8–8.10 show the trained membership functions of the controller.

8.3.3 ANN–FL PSS Using Accelerating Power

Though conventional PSSs using speed deviation have been successfully applied in practical systems, they can cause instability of torsional oscillatory modes[8–24]. One way to overcome this limitation is to use a torsional filter. It is a disadvantage to have to use such a filter which introduces a phase–lag at low frequencies and has a destabilizing effect on the exciter mode. These restrictions may or may not exist in applications of the newly–designed ANN–FL PSSs. Further investigation and practical implementation experience is needed to clarify this point.

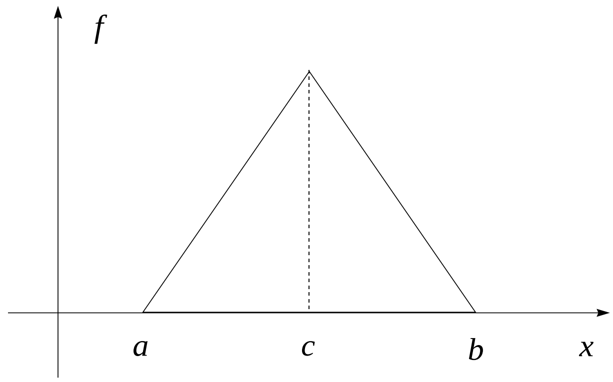

Fig. 8.6 Triangular Membership Function

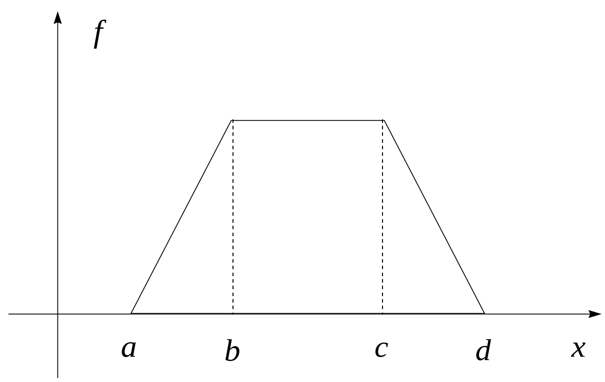

Fig. 8.7 Trapezoidal Membership Function

Table 8.3 Sources of Data Collection

Loading Level(%)	Conventional PSS	
	Speed	Acc. Power
100	scpss1	apcpss1
75	scpss7	apcpss7
50	scpss5	apcpss5
Step(+4%)	sstep1	apstep1

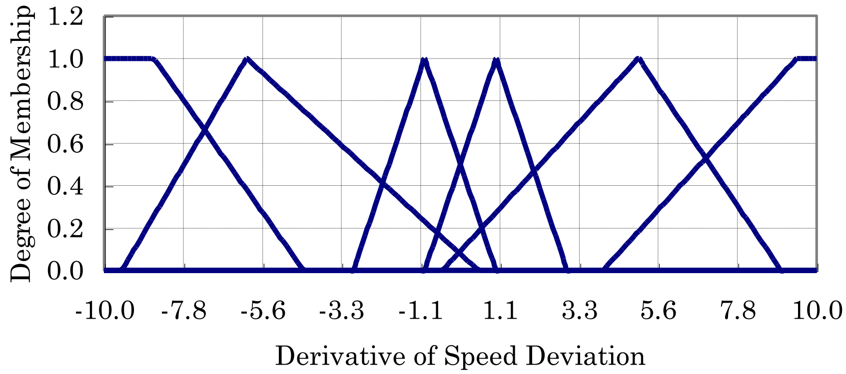

Fig. 8.8 Membership Functions for State Variable $\Delta\omega / \Delta t$

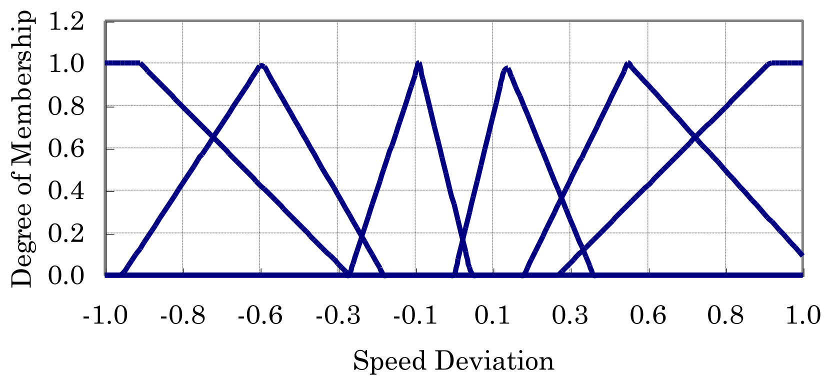

Fig. 8.9 Membership Functions for State Variable $\Delta\omega$

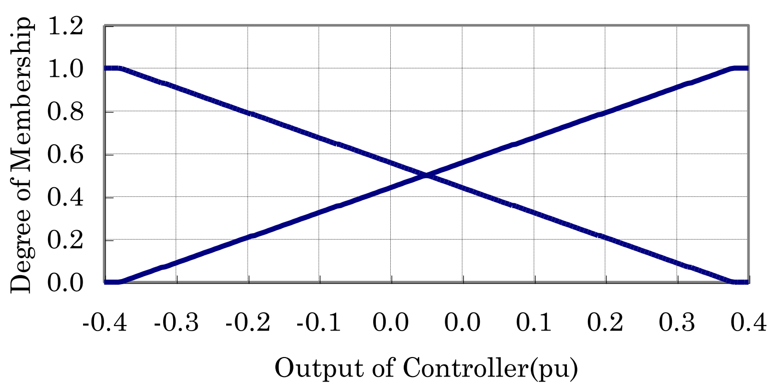

Fig. 8.10 Membership Functions for Output Variable ΔV

To overcome the limitations of the CPSS based on speed deviation, the Delta–P–omega stabilizers have been developed[8–25]. The principle of this stabilizer is illustrated by (8.9) where an equivalent signal to speed deviation has been derived from the accelerating power. This is given by,

$$\Delta\omega_{eq} = \frac{1}{2H}\int(\Delta P_m - \Delta P_e)dt \tag{8.9}$$

where

$2H$ = inertia constant of the machine,

ΔP_m = change in mechanical power,

ΔP_e = change in electrical power, and

$\Delta\omega_{eq}$ = equivalent speed deviation.

Since torsional components are inherently attenuated in the integral of ΔP_e signal, $\Delta\omega_{eq}$ will be free of torsional modes if the ΔP_m component is negligible as in many applications. Otherwise there is a technique to measure the integral of ΔP_m without introducing torsional modes[8–24].

On the basis of similar considerations for designing an accelerating power CPSS, an ANN–FL PSS using accelerating power as the input signal was designed in this research. The design procedure, controller structure and training program are basically the same as those used in designing the speed ANN–FL PSS. Therefore, only its simulation studies will be presented in the following section.

8.4 PERFORMANCE EVALUATION OF THE ANN-FL PSS

8.4.1 General Comments

In this section, a comprehensive investigation of the performance of the two newly–designed ANN–FL PSSs, when applied to the two–machine infinite–bus power system, is reported. Simulation studies were carried out for two different operating conditions, demonstrating the robustness of the PSSs. Specifically, the following categories of disturbances were used in the study: (1) a 4% step reference voltage change, simulating the effect of voltage variation in the system; (2) a 0.25pu step increase of the input power to generator #1, simulating the transients of load variation; and (3) severe three–phase to ground faults at different locations with different switching sequences, simulating transient performance of the various PSSs. Load flow Case A in Tables 8.1 & 8.2 was used unless otherwise stated in the presentation that follows.

8.4.2 Step Reference Voltage Change

To illustrate the dynamic behavior of the power system when it experiences a slight shift of the operating condition from one point to another, a step reference voltage of 4% increase was applied at the terminal bus of G#1. This disturbance causes both transient and steady–state changes in the rotor angle, generated reactive power and terminal voltage of the machine. For the purpose of simulation studies, the transient gain reduction(TGR) of the excitation system of G#1 was disabled in order to make the oscillations more pronounced, so that the advantages of each control scheme can be more readily seen. Due to space limitation, only partial results obtained from the simulations are shown in Figs. 8.11(a) ~ 8.11(d). The following observations include also the results not shown in figures.

- When a generator is required to be operating from one reference voltage to another, say from 1.05 pu to 1.09 pu in this example, it is necessary to generate more reactive power into the system to maintain that desired voltage profile. Figures 8.11(b) & 8.11(c) show that the terminal voltage of G#1 is stabilized at 1.09 pu and the reactive power is raised from 0.7 pu to 1.4 pu in two seconds after the disturbance.

- It is shown in the simulations that the real power of G#1 returned to its original operating point in two seconds after the disturbance(not illustrated). But the power angle is reduced from 30° to 25°, as shown in Fig. 8.11(a).

- The control contribution of the CPSS and the ANN–FL PSS to the stabilization of the oscillations is basically the same; the latter offers a marginal advantage over the CPSS. This is seen from the output of the excitation system shown in Fig. 8.11(d) and from other responses.

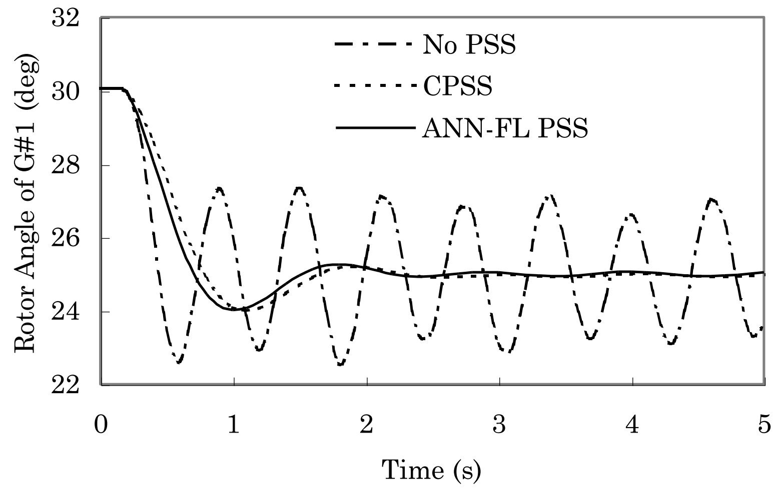

Fig. 8.11(a) Machine Angle Response to A 4% Step Voltage Change

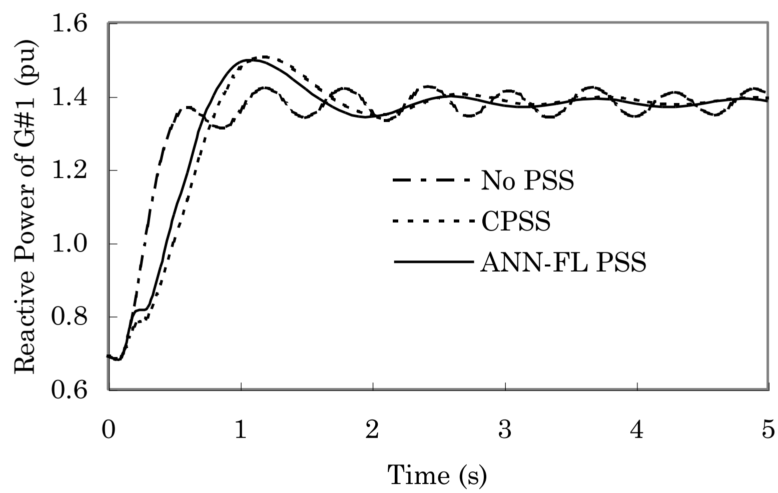

Fig. 8.11(b) Reactive Power Response to A 4% Step Voltage Change

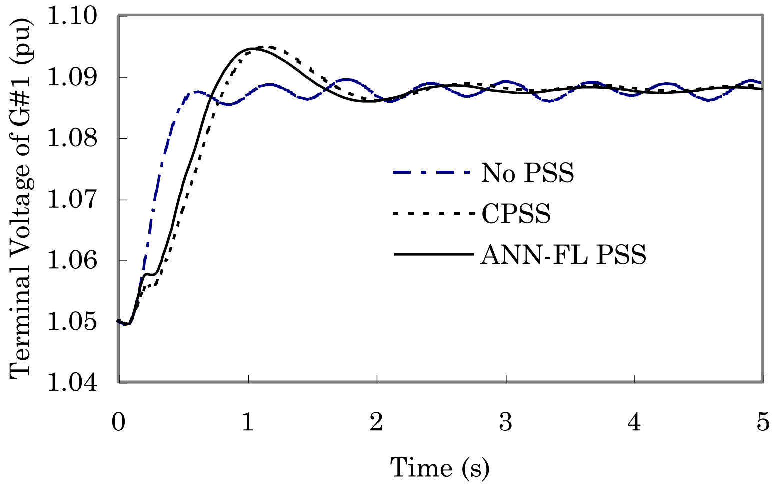

Fig. 8.11(c) Terminal Voltage Response to A 4% Step Voltage Change

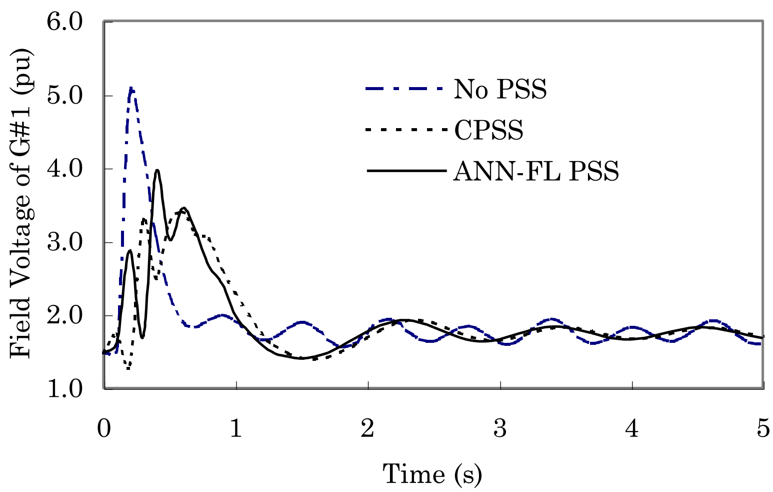

Fig. 8.11(d) Field Voltage Response to A 4% Step Voltage Change

8.4.3 Step Load Change

Load variation is present in every power system. It is intended that the supplementary excitation control can provide a means to accelerate the stabilization process after a sudden load change. To illustrate the performance of the CPSS and the newly–designed ANN–FL PSS under a load disturbance, a step increase of 0.25 pu of the input power was applied to generator #1. In terms of dynamic behavior of the generator, applying this disturbance is equivalent to losing a local load. It causes the machine angle and electric power to shift from the original operating points to new ones. Figures 8.12(a) ~ 8.12(d) show part of the results obtained from three simulations. The following observations are in order:

- Since the input mechanical power is increased by 0.25 pu, the output of the electric power from generator #1 is also increased by the same amount as shown in Fig. 8.12(b), from 1.65pu to 1.90pu. This is equivalent to saying, if the mechanical power is kept unchanged, a sudden loss of 0.25 pu of the local load means that this amount of electric power has to be exported to the system.
- The control action of the ANN–FL PSS is instantaneous as shown in Fig. 8.12(d). Its performance is marginally advantageous over that of the CPSS, as seen in Figs. 8.12(a) & 8.12(c), showing the rotor angle and the terminal voltage response, respectively.

- The local mode oscillation of the electric power was damped out in less than one second (Fig. 8.12(b)). The rotor angle settled down to its new operating point in about two seconds (Fig. 8.12(a)). The terminal voltage experienced a maximum of 1.5% excursion during the first cycle after the disturbance and returned to its original operating point in two seconds. Figure 8.12(c) also shows the inter–area oscillation which can not be seen in Figs. 8.12(a) & 8.12(b) because of the $y-$axis scale. The amplitude of the oscillation is also very small.

8.4.4 Fault Conditions

Power system stabilizers(PSSs) were originally designed to enhance small–signal stability of power systems. At the same time, they should perform satisfactorily under severe transient conditions. Transient stability is defined as the ability of a power system to maintain synchronism when subjected to a large disturbance such as a three–phase to ground fault, loss of generation, or loss of a large load. Under such a fault condition, large excursions of generator rotor angles, power flows and bus voltages can occur.

In the previous two sections, a step voltage change and loss of a fairly large load(0.25pu) were simulated. It has been shown that the newly–designed ANN–FL PSS demonstrated superior performance in the simulation studies. The objective of this section is to illustrate how the ANN–FL PSS performs under severe fault conditions.

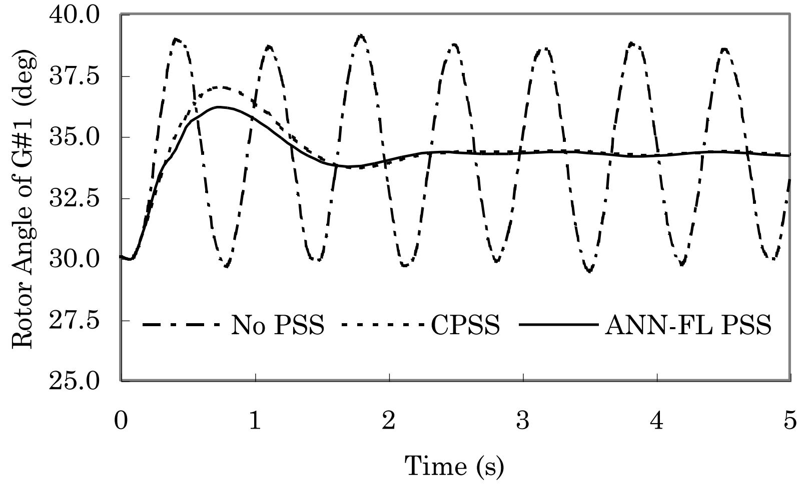

Fig. 8.12(a) Machine Angle Response to A 0.25pu Step Load Change

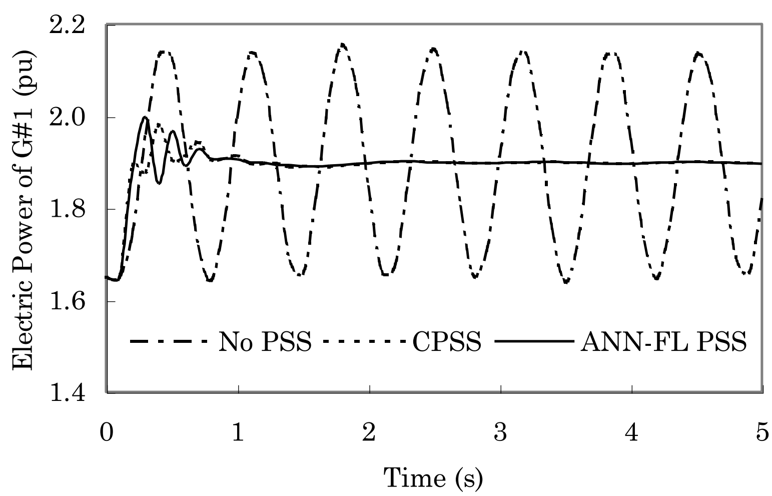

Fig. 8.12(b) Electric Power Response to A 0.25pu Step Load Change

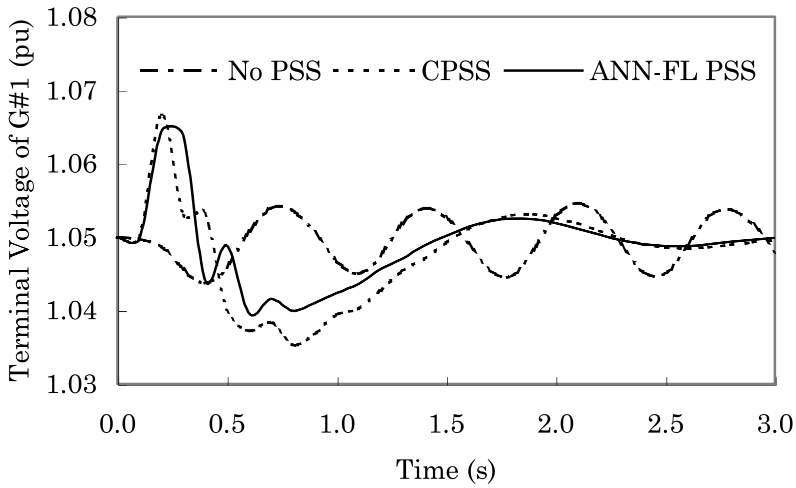

Fig. 8.12(c) Terminal Voltage Response to A 0.25pu Step Load Change

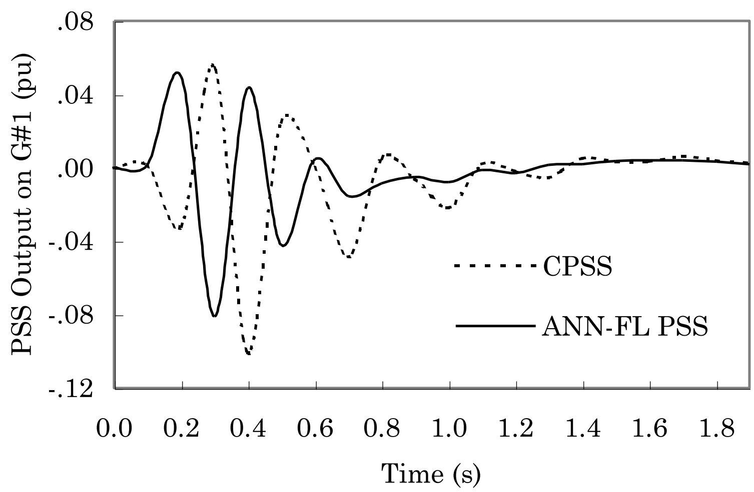

Fig. 8.12(d) Controller Response to A 0.25pu Step Load Change

(1) *Three–Phase Fault on Line 1–2*

With the same system configuration as used in the previous sections, six simulations were conducted of the system when a 6–cycle three–phase to ground fault on the line 1–2 near the terminal bus of generator #1 was applied. The line was restored right after the fault was cleared.

- Figures 8.13(a) & 8.13(b) show the situation where a PSS was activated on generator #1. It can be seen that the ANN–FL PSS provided more damping to the local mode than the CPSS did. The inter–area mode sustains(Fig. 8.13(a)).
- Figures 8.14(a) & 8.14(b) show the situation where each of the two generators was equipped with either the ANN–FL PSS or the CPSS. For the convenience of comparison, the response with only the ANN–FL PSS applied is also included(the fourth curve in each of the two figures). It can be seen that with the ANN–FL PSS on each machine or with the ANN–FL PSS on G#1 and the CPSS on G#2, both the local and the inter–area modes can be damped out in about two seconds.
- For this severe disturbance, one single PSS can not completely suppress the inter–area oscillation as shown in Fig. 8.13(a) and the #4 curve in Figs. 8.14(a) & 8.14(b).

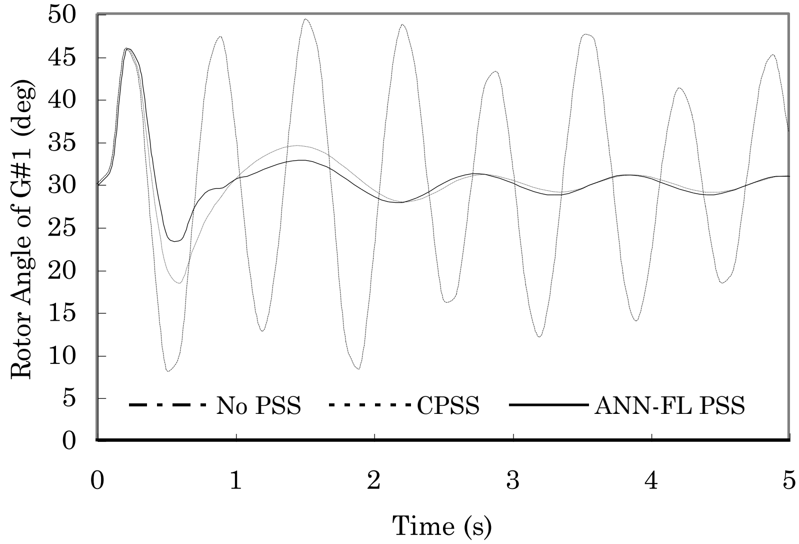

Fig. 8.13(a) Rotor Angle Response to A Three–Phase to Ground Fault at the Terminal Bus of G#1 for 6–Cycles, with One Controller

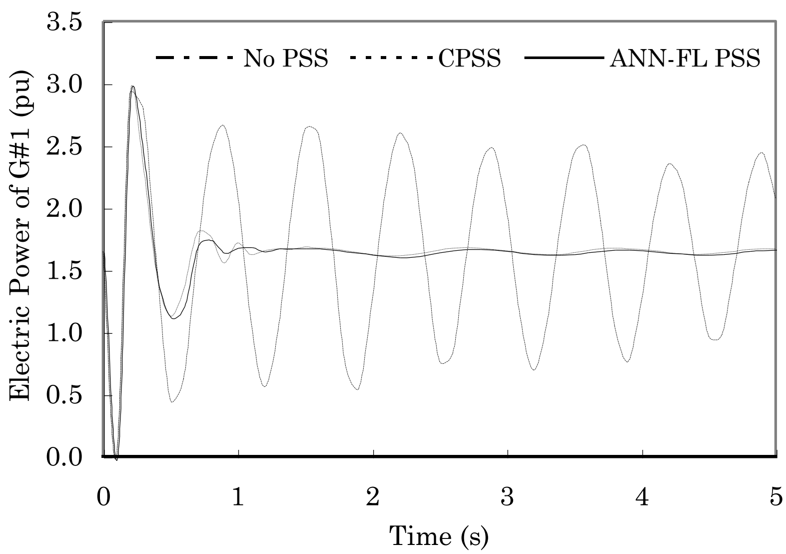

Fig. 8.13(b) Electric Power Response to A Three–Phase to Ground Fault at the Terminal Bus of G#1 for 6–Cycles, with One Controller

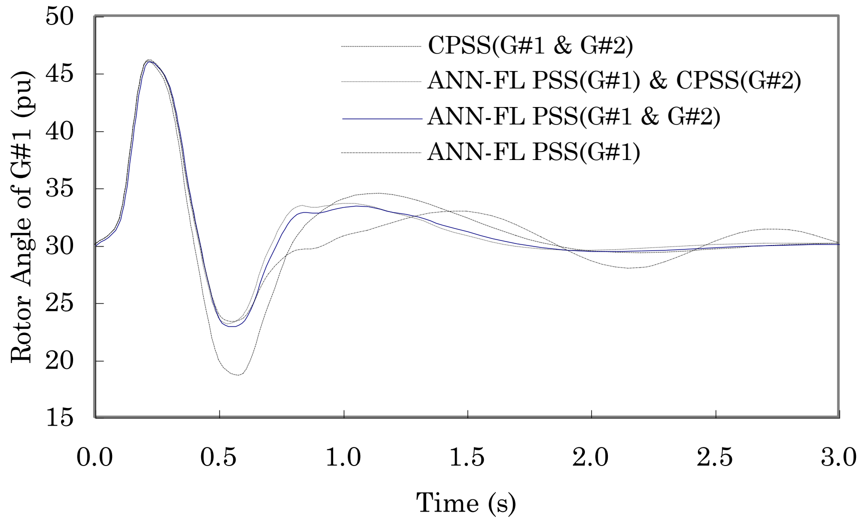

Fig. 8.14(a) Rotor Angle Response to A Three–Phase to Ground Fault at the Terminal Bus of G#1 for 6–Cycles, with Two Controllers

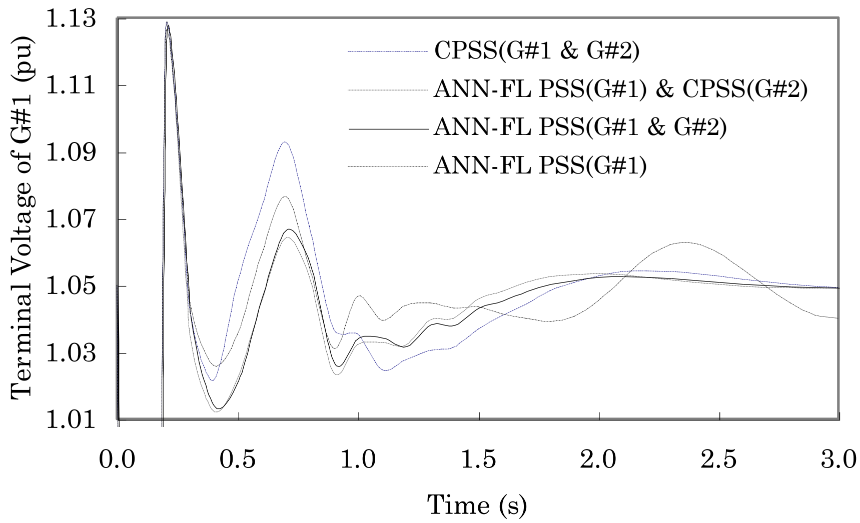

Fig. 8.14(b) Terminal Voltage Response to A Three–Phase to Ground Fault at the Terminal Bus of G#1 for 6–Cycles, with Two Controllers

(2) *Three–Phase Fault on Line 1–4*

The study system was then operated at a condition described by load flow Case B(Tables 8.1 & 8.2). A second three–phase to ground fault was simulated on the line 1–4 near bus #1 for 6–cycles. The line was restored 0.4s after the fault was cleared. Figure 8.15 shows the rotor angle response of G#1 following the disturbance. Three simulations were executed.

- When there is no PSS installed, the generators, and therefore the system, is oscillatorily unstable. When the CPSS is present on G#1, the "overshoot" of the first swing of G#1 is increased substantially as compared with the case of no PSS. With the ANN–FL PSS present on G#1, both the local and the inter–area modes are appreciably damped.

(3) *Three–Phase Fault on Line 2–3*

With the system operating at load flow Case B(Tables 8.1 & 8.2), a third transient condition was simulated with a 6–cycle three–phase to ground on the line 2–3 near bus #2. The line was restored 0.5s after the fault was cleared. Figure 8.16 shows responses of the rotor angle of G#1 following the disturbance.

- As the power transfer on this line was very large(see Case B in Table 8.1 & 8.2), the magnitude of oscillation is quite large. The CPSS provided

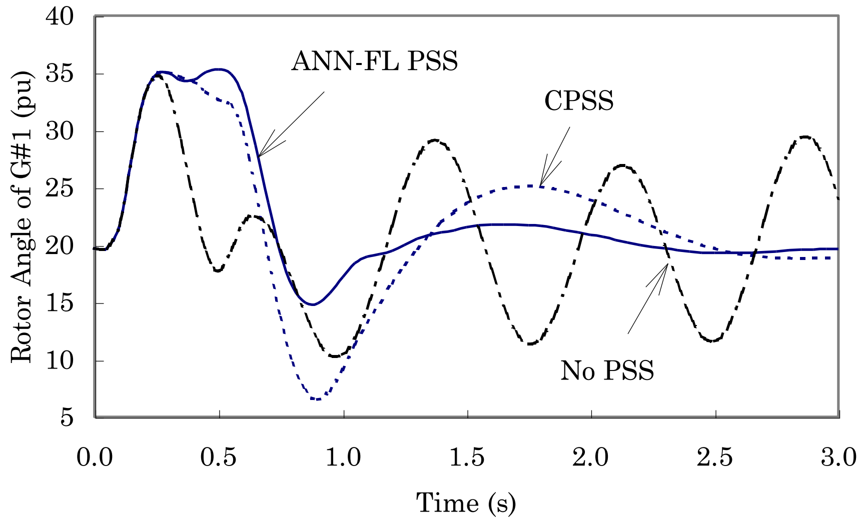

Fig. 8.15 Rotor Angle Response to A Three–Phase to Ground Fault on the Line 1–4 for 6–Cycles

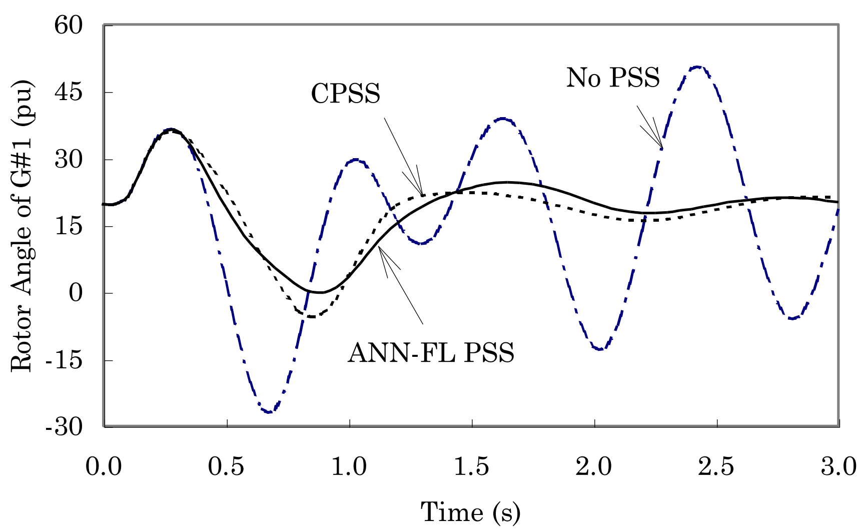

Fig. 8.16 Rotor Angle Response to A Three–Phase to Ground Fault on the Line 2–3 for 6–Cycles

substantial damping to the local mode. The ANN–FL PSS did an even better job(compare the three curves and note the y – axis scale too).

- The oscillation of the inter–area mode is manifest, due to the fact that the faulted line is directly connected to the equivalent machine.

8.4.5 ANN–FL PSS Using Accelerating Power

A transient simulation for the ANN–FL PSS using accelerating power as input signal was carried out. The fault applied was the 6–cycle three–phase to ground fault on line 1–2 at the terminal bus of G#1 as simulated previously. Figure 8.17 shows the rotor angle response of G#1 to the fault and the output of the PSS.

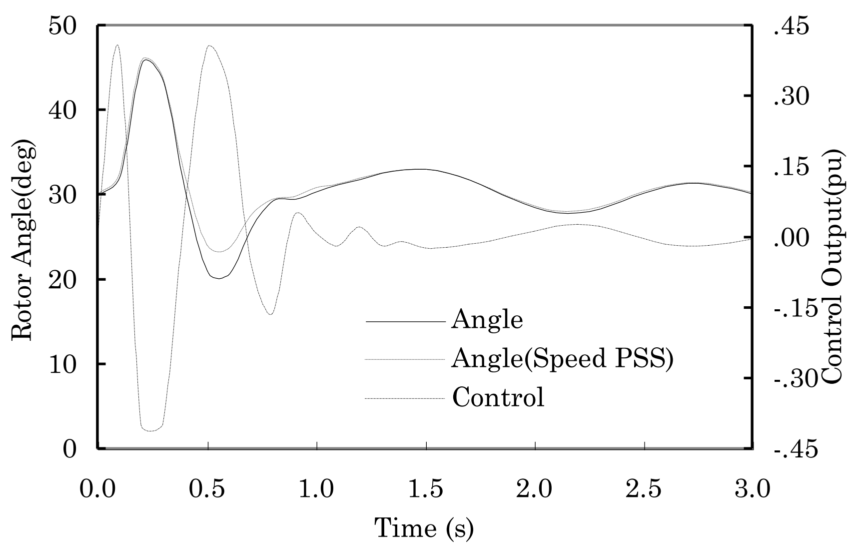

Fig. 8.17 Rotor Angle Response to the Three–Phase to Ground Fault on Line 1–2, with the ANN–FL PSS Using Accelerating Power As Input Signal

- It can be seen that the performance difference of the two ANN–FL PSSs is indistinguishable after the first swing in which the speed ANN–FL PSS produces less “overshoot”.

8.5 SUMMARY

At the beginning of this chapter, an introduction to the enhancement of power system stability has been presented. At present, small– and large–signal stability problems are handled with the use of power system stabilizers (PSSs) which are cost–effective. A brief description of the study system employed in this thesis is given, including its load flow studies, frequency response, and transient simulations. Followed is the design of two ANN–FL PSSs, one using speed deviation as input and the other using accelerating power. The design procedure and the structure of the ANN–FL PSSs are the same as used in Chapter 5. In the last section, performance evaluation is presented of the newly–designed ANN–FL PSSs under different system disturbances.