DESIGN AND PERFORMANCE OF A *LOCAL* GAIN SCHEDULING POWER SYSTEM STABILIZER FOR INTER-CONNECTED SYSTEM

Falguni Ghosh
&
Indraneel Sen
Indian Institute of Science
BANGALORE 560 012

ABSTRACT:

A new 'Gain Scheduling Stabilizer' for interconnected power systems has been described in this paper. The design of ths PSS is based on a priori information about readily available machine and excitation system parameters and 'Observation' for a certain duration of time of the network from the bus of the machine concerned to ascertain the electrodynamic coupling of the machine to rest of the network.

The computational complexity of this PSS requires the use of relatively sophisticated computing system. Though, such computers are now available, they are not in common use in actual power plants. With this in view, the PSS design has been modified so that the adaptive gains are selected in real time based on the operating conditions and worst case network parameters. The modified PSS can be implemented using on-line computers having capabilities similar to those of ordinary PCs or even µP systems with moderate memory and computational capabilities.

KEYWORDS:
Power System Stabilizers, Adaptive Control

INTRODUCTION:

The excitation systems of almost all modern synchronous generators, operating in an inter-connected power system are equipped with high gain, low time constant automatic voltage regulators (AVR). The use of such AVRs, along with increasing utilization of long transmission lines for bulk power. transfer have resulted in an overall lowering of dynamic stability margin of the system. This is manifested in the form of poorly damped low frequency oscillations of individual units with respect to the rest of the system., or worse still, of one group of coherent units with respect to another coherent group.

The stability of the system, in principle, can be considerably improved by the application of close-loop feedback control. Over the years, a considerable amount of research has been directed towards designing suitable Power System Stabilizers (PSS). Designing and tuning stabilizers are complex processes. A majority of stabilizers in use are of 'fixed gain' type, which are tuned by a combination of off-line mathematical modelling and field trials. Due to nonlinear nature of the plant and continually changing loading pattern, network element values and topology of the network, the performance of these stabilizers can be considerably degraded. In recant years, a number of methods for designing 'Adaptive or Self Tuning Stabilizers' have been proposed. These include PSS based on model identification techniques[1-2] Gain scheduling PSS with precomputed gains stored in look-up tables[3] and PSS to cancell the negative damping contribution of the AVR[4].

Most of these stabilizers are computationally complex and often impossible to implement in real time with the moderate computational facilities available in modern power plants. The gain scheduling PSS describe? in this pager takes advantage of the a priori knowledge available about the system and combined with a simple on-line identification of the external reactance X_e, enables gain scheduling most appropriate to the then system and operating conditions.

THE PSS **DESIGN** PHILOSOPHY:

A particular generating unit, operating in a multimachine environment is modelled as a single machine connected to an infinite bus (SMIB) through a transmission line. However, unlike in an actual SMIB case, the changing network element values, tha loading pattern of the other machines and the topology of the network beyond the machine concerned are made to reflect as a variable transmission line impedance (as opposed to the fixed impedance in SMIB case). As the machine and excitation parameters arc known and the terminal quantities can be measured easily, the PSS gains could be selected as soon as the variable line impedance is known. It is for the estimation of this variable impedance, the network has to be observed from the terminals of the concerned generator.

The PSS chosen has the form $k_p \Delta P + k_w \Delta w$. The adaptive gains k_p and k_w are determined by instantaneous operating conditions and the transmission line impedance 'seen' by the machine and are obtained by local real time measurements at each machine. This is a truly adaptive PSS with excellent performance. However, since most of the on-line parameter identification techniques used in implementing gain scheduling PSS including the proposed new PSS require observation of the system after the disturbance has been initiated, there may be a considerable time delay between the disturbance initiation and the actual control action. To eliminate this delay, in the practical implementation of the proposed PSS, the on-line Z_e estimation has been replaced by an off-line estimation of the 'worst' case Z_e. This Z_e estimation process can be run as often as desired or even as a background process on the computer.

The PSS thus operates in semi-adaptive mode with the gains now determined by the instantaneous operating conditions and the worst case transmission line impedance. The k_p and k_w values are obtained by detailed machine models to generate k_p and k_w surfaces in P-Q plane for worst case impedance Z_e. Finally, only the polynomial coefficients to regenerate these surfaces are stored in an on-line computer so that the gains k_p and k_w at any particular operating point can be easily computed using vector-matrix multiplications. Use of off-line computations to estimate the polynomial coefficients have also helped to reduce the on-line memory requirement otherwise needed for storing a huge number of gain values in a look-up table. However, this involves additional computational burden on the real-time computer.

Z_e IN MULTI-MACHINE ENVIRONMENT :

The actual system is represented in Fig. 1A and the modelled system in Fig. 1B. It may be noted that it is impossible to compute the model transmission line impedance Z_e solely from measurements made at the generator bus unless some assumptions are made about the remote fictitious bus. Assuming that the voltage of the fictitious bus is 1.0 pu and Z_e has a given X/R ratio, it is possible to obtain a quadratic expression for X_e (imaginary part of Z_e) [Appendix: 1] in terms of the operating point P_{to}, Q_{to} and V_{to} at the generator terminal. By monitoring these quantities at the generator terminal over a wide range of operating conditions, it is possible to estimate the range of Z_e values as 'seen' by the particular unit concerned.

For an SMIB model with the machine operating with P_{to}, Q_{to} at the generator terminal, it is well known that higher the transmission line reactance X_e, poorer is the electro-dynamical coupling between the machine and the infinite bus. In other words, a higher transmission line impedance in an SMIB model is detrimental from dynamic stability point of view. Therefore, out of the entire range of Z_e values as observed from the machine terminal over a period of time, the maximum value of Z_e (hence maximum X_e) is chosen to represent the electro-dynamic coupling of the machine to the fictitious bus, since it can be expected to represent the 'worst case' situation of dynamic stability of the particular unit.

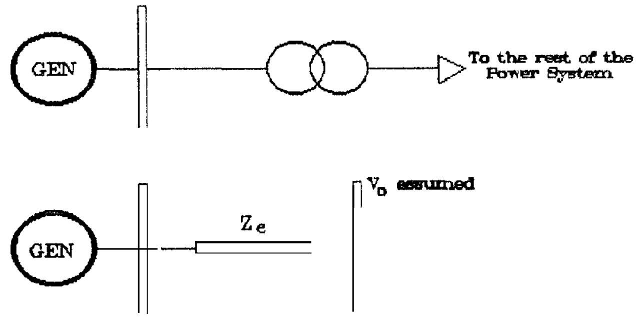
THE k_p AND k_w SURFACES:

With the 'worst case Z_e' available from the system data observed over a certain duration of time, it is now possible to model the system as a linearized SMIB model for any particular operating point P_{to}, Q_{to}. For a realistic operating range of a generating unit given by,

$$0.10 \le P_{to} \le 1.10 \quad \text{and} \quad -0.20 \le Q_{to} \le 0.80 \qquad ..(1)$$

we can have $(n+1)_*(n+1)$ operating points, about each of which the SMIB model can be linearized, where n denotes the number of small incremental steps into which the P_t and Q_t ranges have been divided. For each of these $(n+1)_*(n+1)$ operating points, the eigenvalues of the SMIB model are checked with $(k_p * \Delta P)$ and $(K_w * \Delta w)$ stabilizers with k_p decreased in small steps from zero and k_w increased in small steps from zero, till the rightmost eigenvalue of the linearized system stop moving towards the left. The corresponding values of k_p and k_w are the chosen gains of the PSS at that particular operating point. This off-line exhaustive method of searching for k_p and k_w for every operating point, results in gain-surfaces represented by $(n+1)_*(n+1)$ points in the P_{to}-Q_{to}-k_p and P_{to}-Q_{to}-k_w spaces.

The fundamental aspect of 'tuning' by this method is that the decay rate, i.e. the negative of the real part of the eigenvalue of the least damped mode, is maximized. This technique has long been recognized as one of the methods of tuning a PSS[5]. A major advantage of tuning by this method is that since attention is always focused on the 'least damped' mode, it prevents the exciter or any other modes from becoming unstable while trying to stabilize the rotor mode.



$$u = \frac{P_{to} - P_{tmin}}{P_{tmax} - P_{tmin}} \qquad \text{where } P_{tmax} = 1.10 \text{ pu and } P_{tmin} = 0.10 \text{ pu}$$

$$v = \frac{Q_{to} - Q_{tmin}}{Q_{tmax} - Q_{tmin}} \qquad \text{where } Q_{tmax} = 0.80 \text{ pu and } Q_{tmin} = -0.20 \text{ pu} \qquad ..(2)$$

The gains k_p and k_w can be expressed as,

$$k_p = f_p(u,v) = \sum_{i=0}^{(N_1-1)} \sum_{j=0}^{(N_2-1)} a_{ij} u^i v^j$$

$$k_w = f_w(u,v) = \sum_{i=0}^{(M_1-1)} \sum_{j=0}^{(M_2-1)} b_{ij} u^i v^j, \quad u,v \in [0,1] \qquad ..(3)$$

The values of N_1, N_2 (M_1, M_2) depend on the extent of nonlinearity of k_p (k_w) and the acceptable level of accuracy of the curve fitting desired. Once, N_1, N_2 (M_1, M_2) are decided upon, the polynomial coefficients a_{ij} (b_{ij}) for k_p (k_w) are to be determined. This is done by solving a set of $N_{1*}N_2$ $(M_{1*}M_2)$ linear equations involving $N_{1*}N_2$ $(M_{1*}M_2)$ unknowns. The system of linear equations has the form,

$$[EKP][a] = [KP] \qquad ..(4a)$$
$$[EKW][b] = [KW] \qquad ..(4b)$$

where [EKP] ([EKW]) is an N_*N (M_*M) non-singular square matrix generated by the normalized operating points u_i, v_j, with $i = 1, 2, .. N_1 (M_1)$ and $j = 1, 2, ... N_2$ (M_2) and $N = N_{1*}N_2$ $(M = M_{1*}M_2)$.

[KP] and [KW] are column vectors of lengths N and M respectively, containing the computed gains. [a] and [b] are column vectors containing the unknown coefficients a_{ij} and b_{ij} respectively.

The expanded version of eqn. (4a), for example, looks like,

$$u_0^{N1-1}v_0^{N2-1}a_{N1-1,N2-1} + u_0^{N1-1}v_0^{N2-2}a_{N1-1,N2-2} + \dots + a_{00} = f_p(u_0,v_0)$$

$$u_1^{N1-1}v_0^{N2-1}a_{N1-1,N2-1} + u_1^{N1-1}v_0^{N2-2}a_{N1-1,N2-2} + \dots + a_{00} = f_p(u_1,v_0)$$

$$u_{N1-1}^{N1-1}v_{N2-2}^{N2-1}a_{N1-1,N2-1} + u_{N1-1}^{N1-1}v_{N2-1}^{N2-2}a_{N1-1,N2-2} + \dots + a_{00} = f_p(u_{N1-1},v_{N2-1})$$

The values of $f_p(u_i,v_j)$ and $f_w(u_i,v_j)$ are either the actual gains computed by the tuning algorithm already described (when $N_1,N_2=n+1$) or interpolated values from best-fit curves (when $N_1,N_2 < n+1$).

For a realistic SMIB machine-excitation system model, it was found that $N_1=N_2=7$ as also $M_1=M_2=7$, results in polynomial fittings with acceptable errors. Therefore, for a given worst case Z_e, only 49 algebraic coefficients for each k_p and k_w gains need to be computed end stored in the real-time computer. For any operating point within the range of operation specified in (1), the gains k_p and k_w can be simply computed by,

$$k_p = [u][AKP][v]^t \qquad k_w = [u][AKW][v]^t \quad ..(5)$$

where [AKP] and [AKW] are the 7x7 matrices containing the algebraic coefficients

$$AKP_{ij} = a_{7-i,7-j} \quad AKW_{ij} = b_{7-i,7-j}, \quad i=1,2,..7$$

$$\text{and,} \quad [u] = [\,u^6 \;\; u^5 \;\; u^4 \;\; u3 \;\; u^2 \;\; u \;\; 1\,],$$

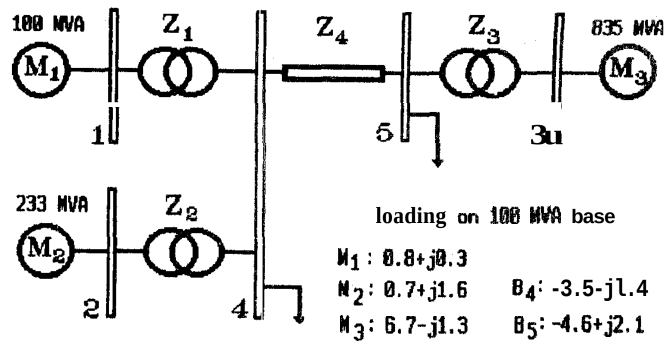
$$[v] = [\,v^6 \;\; v5 \;\; v^4 \;\; v3 \;\; v^2 \;\; v \;\; 1\,] \quad ..(6)$$

RESULTS:

A dynamic flux-linkage multimachine model is used for the purpose of studies. The configuration is shown in Fig.2 and the machine and system parameters are given in Appendix-2. Widely different machine ratings were intentionally chosen so as to highlight the performance of the PSS on both small as well as very large machines. Each unit is represented by a 10th order dynamical model consisting of a 7th order synchronous generator, 1st order AVR. 1st order turbine and 1st order governor.

For the purpose of PSS design, the possible operating range of each machine is chosen as given in eqn (1), and the ranges of P_t and Q_t were divided into 10 steps each. Thus for each machine, k_p and k_w were computed for 121 different points in the $P_t - Q_t$ plane. The 'tuning' was carried out with incremental steps of 0.02 and 1.0 for k_p and k_w respectively. The computed k_p and k_w surfaces (top) and the corresponding synthesized surfaces (bottom) at same resolution are shown in Fig.3.

The multimachine model was subjected to a wide range of operating conditions by changing the machine loadings as well as the loads on bus 4 and 5, and for each of those operating points, Z_e estimations were done from bus 1, 2 and 3. A sample of those results are given in Table 1. As evident from the table, for any particular unit the worst case Z_e occurs when



MULTI-MACHINE CONFIGURATION

Fig. 2 System Configuration for PSS analysis

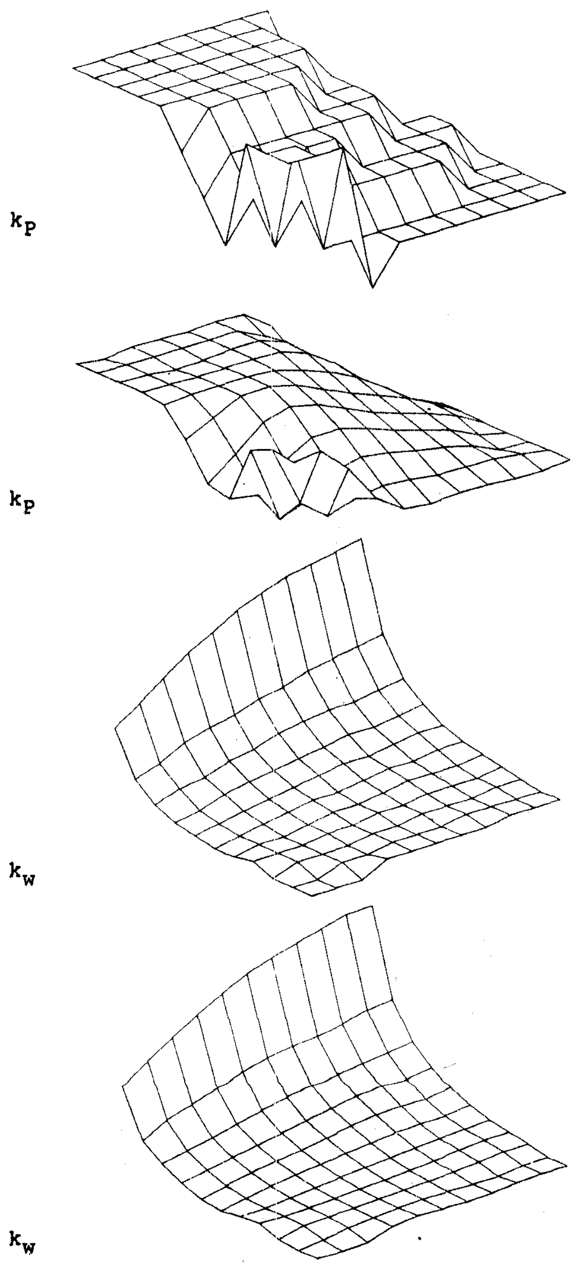


Fig.3 The k_p and k_w surfaces for worst case Z_e

it is supplying a high active power (P_t), but with a negative reactive power (Q_t) generation. This is expected, since under these circumstances a unit is known to be most weakly coupled to the rest of the network.

With the knowledge of worst case Z_e and the machine parameters for each unit, stabilizers were designed for each of the three units. Sample time response plots of change in active power following pulse disturbances at V_{ref} points of each of the three machines, with and without PSS, are shown in Fig.4.

Table 2 (A, B and C) shows the eigenvalues of each of the three machines with and without the proposed PSS for some typical operating points. The identification of the rotor and exciter modes was done using the 'Participation Matrix technique'. It is obvious from the eigenvalue tables, that with the proposed FSS in action, the damping of each machine has considerably improved, while, in general, there is hardly any detrimental effect on the synchronizing torques.

TABLE - 1

Machine #1		Machine #2		Machine #3		X_{e1}	X_{e2}	X_{e3}
P	Q	P	Q	P	Q			
(pu)		(pu)		(pu)		pu	pu	pu
0.80	0.30	0.80	0.30	0.80	0.30	0.07818	0.09281	0.10884
0.80	***-0.15***	0.80	0.30	0.80	0.30	***0.13992***	0.09281	0.10884
0.30	+0.70	0.80	0.30	0.80	0.30	0.09632	0.09281	0,10884
0.30	0.20	0.80	0.30	0.80	0.30	0.08829	0.09281	0.10884
0.30	-0.10	0.80	0.30	0.80	0.30	0.12887	0.09281	0.10884
0.80	0.30	***0.80***	***-0.15***	0.80	***0.30***	0.07818	***0.16364***	0.10884
0.80	0.30	0.30	0.70	0.80	0.30	0.07818	0.11553	0.10884
0.80	0.30	0.30	0.20	0.80	0.30	0.07818	0.10580	0.10884
0.80	0.30	0.30	-0.10	0.80	0.30	0.07818	0.15359	0.10884
0.80	0.30	0.80	0.30	***0.80***	***-0.15***	0.07818	0.09281	***0.18963***
0.80	0.30	0.80	0.30	0.30	0.70	0.07818	0.09281	0.13718
0.80	0.30	0.80	0.30	0.30	0.20	0.07818	0.09281	0.12550
0.80	0.30	0.80	0.30	0.30	-0.10	0.07818	0.09281	0.18130
0.73	-0.20	0.73	0.39	0.81	0.39	0.12917	0.10073	0.11586

TABLE - 2A
Eigenvalues of Machine # 1
(R : Rotor Mode, E : Exciter Mode)

Network Loading	Without PSS	With PSS
1	R : -1.129 ± j8.172	R : -2.855 ± j3.849
		R : -3.189 f j9.894
	E : -4.327 ± j0.399	E : -2.855 f j3.849
2	R : -0.887 f j6.544	R : -2.981 f j5.041
	E : -5.354 f j1.859	E : -3.574 f j7.354
3	R : -0.989 ± j7.750	R : -2.999 ± j9.419
	E : -4.375 ± j0.350	E : -3.132 ± J2.859
4	R : -1.123 ± j8.172	R : -3.222 f j9.855
		R : -2.873 i j3.845
	E : -4.300 ± j0.397	E : -2.873 f j3.845

TABLE - 2B
Eigenvalues of Machine # 2
(R : Rotor Mode, E : Exciter Mode)

Network Loading	Without PSS	With PSS
1	R : -0.594 ± j7.183	R : -1.167 ± j5.685
	E : -6.286 ±j14.748	E : -4.490 ±j17.838
2	R : -0.902 ± j7.408	R : -2.981 f j5.041
		R : -1.074 ± j5.515
	E : -6.301 ij14.758	E : -4.517 ij17.842
3	R : -0.940 f j6.292	R : -1.794 f j5.245
	E : -6.120 fj16.195	E : -3.865 fj16.952
4	R : -0.787 ± j6.578	R : -1.563 ± j6.181
	E : -6.105 ±j15.205	E : -5.093 ±j16.526
	E : -6.116 fj14.861	E : -5.222 kj16.663

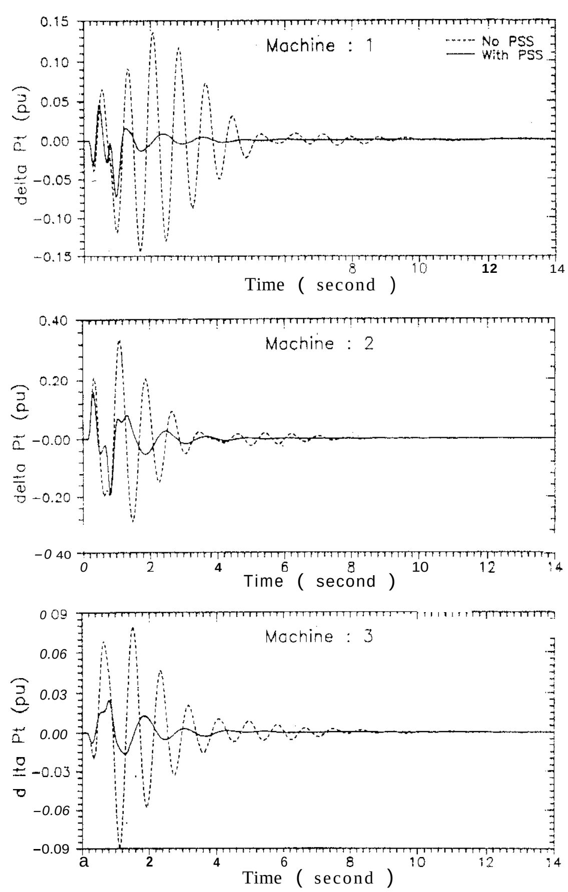


Fig.4 ΔP response with and without the PSS

TABLE - 2C
Eigenvalues of Machine # 3
(R : Rotor Mode, E : Exciter Mode)

Network Loading	Without PSS	With PSS
1	R : -0.218 ± j1.952	R : -0.336 ± j2.061
	E : -4.294 ±j20.514	E : -4.069 ±j27.316
2	R : -0.221 ± j1.956	R : -0.331 ± j2.061
	E : -4.436 ±j20.524	E : -4.275 ±j27.091
3	R : -0.224 ± j1.961	R : -0.457 ± j2.106
	E : -4.284 ±j20.740	E : -4.428 ±j26.997
4	R : -0.242 ± j1.966	R : -1.563 ± j6.183
		R : -0.498 ± j2.066
	E : -5.134 ±j21.706	E : -4.623 ±j21.829

CONCLUSIONS:

This paper has described the designing technique of a simple gain scheduling PSS based on machine parameters and observations of the external network from the machine bus at various loading conditions. The PSS design essentially involves off-line tuning at different operating points using a linearized high order SMIB model. and solving a system of linear equations. Therefore the real. time computational load is reduced to simple vector matrix multiplications. The PSS has been tried out on a multimachine model for a wide range of operating conditions with machine ratings ranging from 100 MVA to 835 MVA, and the results arc quite encouraging.

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APPENDIX - 1

Let us suppose that the X/R ratio of the model transmission line of impedance Z_e (R_e+jX_e) is k. Then it can be shown that, for a SMIB model with negligible local load at generator bus,

$$AX_e^2 + BX_e + C = 0, \quad \text{where } A = I_a^2(1 + 1/k^2)$$

$$B = 2V_tI_a(\sin \phi_t - \cos \phi_t / k)$$

$$C = (V_t^2 - V_\infty^2)$$

V_∞ = 1.0pu (assumed voltage of remote fictitious bus)

V_t = Measured pu voltage at generator bus
I_a = Measured pu line current at generator bus
ϕ_t = p.f angle at generator bus.

For normal operating values of P_t, Q_t, and V_t we get two real values of X_e (i.e. $B^2 - 4AC \geq 0$), and the least positive value is selected since the other value of X_e (if positive) is normally found to be very-high (0.70pu or higher)

Appendix - 2

a. Machine Data (Self Base) :

	M#1	M#2	M#3
MVA :	100	233	a35
Rfd :	0.000686	0.000927	0.001186
Xd :	1.180000	1.569000	2.183000
Xq :	1.050000	1.548000	2.157000
Xad :	1.105000	1.365000	1.937000
Xaq :	0.975000	1.344000	1.511000
M (sec) :	9.970000	8.244640	5.284790

b. AVR Data :

	M#1	M#2	M#3
Ka :	45.00	250.00	250.00
Ta (sec) :	0.09	0.05	0.05

c. Turbine Data :

	M#1	M#2	M#3
Kh :	1.00	1.00	1.00
Th (sec) :	0.50	0.55	0.60

d. Governor Data :

	M#1	M#2	M#3
Kg :	15.00	20.00	20.00
Tg (sec) :	0.20	0.25	0.30