Assessment of Excitation Control by Simulation

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Introduction

The manufacturers and suppliers of large power generation equipment are required to describe the controllers for prime movers and excitation equipment within the scope of their supply. Occasionally, there is the additional responsibility placed on the manufacturer and included in a contract for new plant, to carry out power system studies which incorporate the new plant. The motivation for a manufacturer to develop a facility for modelling and simulation of power system transients arises from at least 4 needs:-

i. The need to provide models of prime movers and excitation system controllers to third parties for their use in power system studies

ii. The need to demonstrate the effectiveness of modulating control to potential customers in developing markets in competition with established, indigenous suppliers, or where historically, the market has been dominated by one or two preferred foreign suppliers.

iii. The need to illustrate the transient/dynamic performance effects of new governors and voltage regulators furnished as part of a power station upgrade.

iv. The need to demonstrate the potential advantages of novel control techniques which can be adopted on existing and new generating plant to the authorities responsible for ensuring stable and reliable generation and transmission of electric energy.

Outline of Method for Simulation

The method for power system transient simulation adopted by Siemens Power Generation Ltd. (SPGL) since 1991 was largely inspired by the approach described by R Podmore and R J Fleming (ref. 1) as long ago as 1974. The paper describes a computer program, written in FORTRAN IV, in which the emphasis is placed on flexibility in the modelling of generators and controllers. Power plant is modelled using differential equations, based on block diagram representations, and the solution of the loadflow problem is algebraic. At the time, the application of the program was limited to small/medium sized networks by run times. This satisfies the needs from a manufacturer's point of view. The approach allows us to concentrate on what we know about whilst enabling most of the characteristics of actual transmission systems, relevant to the effects of prime mover control on transients, to be represented. This is in contrast to the needs of large utilities whose responsibilities require the study of large networks, who need detailed knowledge of alternative network structure and data, and also have the sometimes difficult task of getting data for generator controllers to fit the limited range of structures allowed by the available power system analysis software.

Podmore and Fleming's method uses a general loadflow solution program and a second Fortran program for the calculation of transients. The main tasks of the second program are the reduction of the order of network admittance matrices by removal of non-machine bus bars, setting of data for machines and their controllers, and the calculation of a specified transient by solution of the combined differential/algebraic equations of the system.

The method used by SPGL is similar but exploits the features of Matlab/Simulink for modelling and simulation using block diagram representations of machines and controllers.

Computer Program for Loadflow Solution (LF)

A computer program in Fortran 77 was written to solve the loadflow problem. The program is rather primitive in that it runs on a PC under DOS and has no graphical input or output. It does include the main features otherwise required for a loadflow solution:-

> Lumped parameter representations of transmission lines and tap changing transformers
> Bus types:
>> 0 - the 'slack' or reference bus
>> 1 - load bus bars, at which voltages are to be determined
>> 2 - bus bars at which voltages are specified, corresponding to machines with automatic voltage regulators
>> 3 - bus on a tap changing transformer with specified voltage to be achieved by altering tap settings during the loadflow solution
>> Ground bus - bus number 0 - to allow connection of shunt loads

Tables 1 and 2 provide examples for bus data and bus results for the IEEE 14 bus system (ref. 2).

Multi-machine Transient Computer Program (TS)

The loadflow program provides the steady state, initial condition imposed at the machine terminals. The multi-machine transient computer program, also written in Fortran 77, was intended to set up network switching and fault conditions, import data on the machines and their controllers, and then calculate the resulting transient response. However, the Company had recently purchased a version of MathWorks' Matlab software, with the then newly introduced graphical interface, Simulink. Simulink allows rapid construction of models in the form of block diagrams. It was quickly realised that it would be better to use this method for the representation of generators and controllers, and to exploit Matlab's range of alternative differential equations solvers and features for graphical presentation of results. The function of the TS program was therefore limited to the preparation of network data required by the Matlab/Simulink model of the machines, controllers and network.

The TS program reads the loadflow data and results and re-constructs the complete network admittance matrix. It then allows a sequence of disturbances to be specified. None or more of the following types of disturbance can be set at each given time:-

1 Bus short-circuit
2 Line addition
3 Line removal
4 Transformer addition
5 Transformer removal
6 Machine breaker opened

7 Machine breaker closed

On completion of each disturbance specification, TS outputs a modified admittance network and a reduced order admittance matrix which results from the elimination of load busses, using a matrix arithmetic equivalent of star-delta transformation. A typical sequence possible is - no disturbance (initial conditions); short-circuit at generator transformer HV bus; removal of short-circuit, with simultaneous disconnection of a line.

Matlab/Simulink Model of a 4 machine System

The single line diagram of figure 1 is based on an actual Island power system which has an undersea cable connection to the mainland. Figure 2 is the corresponding 'top level' Simulink representation. The structure of the diagram is similar whatever the number of machines. Each machine supplies 2 axis components of voltage and a load angle to a Matlab function, 'network'. This function uses the appropriate reduced order admittance matrix during a transient to determine the currents drawn from each machine bus. The hierarchical structure of each machine is revealed in detail by expansion of icons through successive layers of the model. That of 'Unit 8', one layer down, is shown in figure 3. Unit 8 has a 'type 2' generator, one with transient and sub-transient saliency in both direct and quadrature axes. A block diagram representation is possible (see ref. 3 for example) but it is preferable to use an S-function model (figure 4). This is a MATLAB function of a prescribed structure in which the differential equations and relationships between inputs/outputs and state variables are listed.

The excitation system model for unit 8 represents a thyristor converter with an AVR and VAR limiter. The model allows step inputs to be applied to the voltage reference and an input from alternative power system stabilisers (PSS). The Matlab/Simulink representation allows alternative controller parameters to be set. It main advantage over proprietary power systems analysis software is the relative ease with which alternative controller structures can be examined.

One other feature of the Matlab/Simulink environment should be mentioned. Signals may be exported to the 'workspace' (memory) during the solution of the transient. These may be post-processed and results presented on graph plots which, in turn, may be pasted into word processor documents for reports. Figure 5 is an example of a plot of all the bus voltages for a 200 mS short-circuit on the 33 kV bus bar (bus 4). These are calculated by injection of the machine bus currents - obtained from the transient solution - into the sequence of complete (inverted) admittance matrices provided by program TS.

Dynamic Stability from Eigenvalue Analysis

The original 4 machine Island system model was constructed to study the effects of adding a new generator (machine no. 2) upon the transient stability of the power system. A detailed representation of the excitation system, including the limits imposed by ceiling voltage and those in the AVR is essential for this purpose. Once the steady state initial operating conditions have been set, all the information required to define the state space equations is available from the file which displays the Simulink diagram. Only three Matlab script statements are required to obtain eigenvalues for the linearised, state space model of the system:-

[sys,x0]=mc4asty([],[],[],0); % returns x0, the initial (operating point) values of state variables

[A,B,C,D]=linmod('mc4asty',x0); % returns A,B,C and D state matrices, after linearisation
[VECT,VALS]=eig(A); % returns eigenvalues and eigenvectors

For demonstration purposes only, an experimental 'power system stabiliser' (PSS), one that derives acceleration from generator power output, was added to generator 2 (figure 6). The PSS can be turned on and off by re-setting a gain to zero. Results with- and without the PSS engaged are given in table 3. The damping of the 'inter-area' mode is much increased but the two other, higher frequency modes are hardly effected, indicating better tuning of the PSS for these modes is necessary.

References

1. Power-System Dynamic-Simulation Program
R Podmore and R J Fleming
Proc. IEE, Vol. 121, No. 10, October 1974 pp 1165-1167

2 Investigation of the Load-Flow Problem
L L Freris and A M Sasson
IEEE Proceedings, Vol. 115, No. 10, pp 1459-1470, October 1968

3. Validation of Synchronous Machine Models and Derivation of Model Parameters from Tests
F P de Mello and L H Hannett
IEEE PAS-100, 1981 pp 662-672

BUS DATA:
IEEE 14 BUS DATA AS FROM GLOVER FILE

NO.	TYPE	V	DELTA	PG	QG	PL	QL	QGMAX	QGMIN
1	0	1.060	0.0	---	---	---	---	---	---
2	2	1.045	---	0.400	---	0.217	0.127	0.500	-0.400
3	2	1.010	---	0.000	---	0.942	0.190	0.400	0.000
4	1	---	---	0.000	0.000	0.478	-0.039	---	---
5	1	---	---	0.000	0.000	0.076	0.016	---	---
6	2	1.070	---	0.000	---	0.112	0.075	0.240	-0.600
7	1	---	---	0.000	0.000	0.000	0.000	---	---
8	2	1.090	---	0.000	---	0.000	0.000	0.240	-0.060
9	1	---	---	0.000	0.000	0.295	-0.024	---	---
10	1	---	---	0.000	0.000	0.090	0.058	---	---
11	1	---	---	0.000	0.000	0.035	0.018	---	---
12	1	---	---	0.000	0.000	0.061	0.016	---	---
13	1	---	---	0.000	0.000	0.135	0.058	---	---
14	1	---	---	0.000	0.000	0.149	0.050	---	---

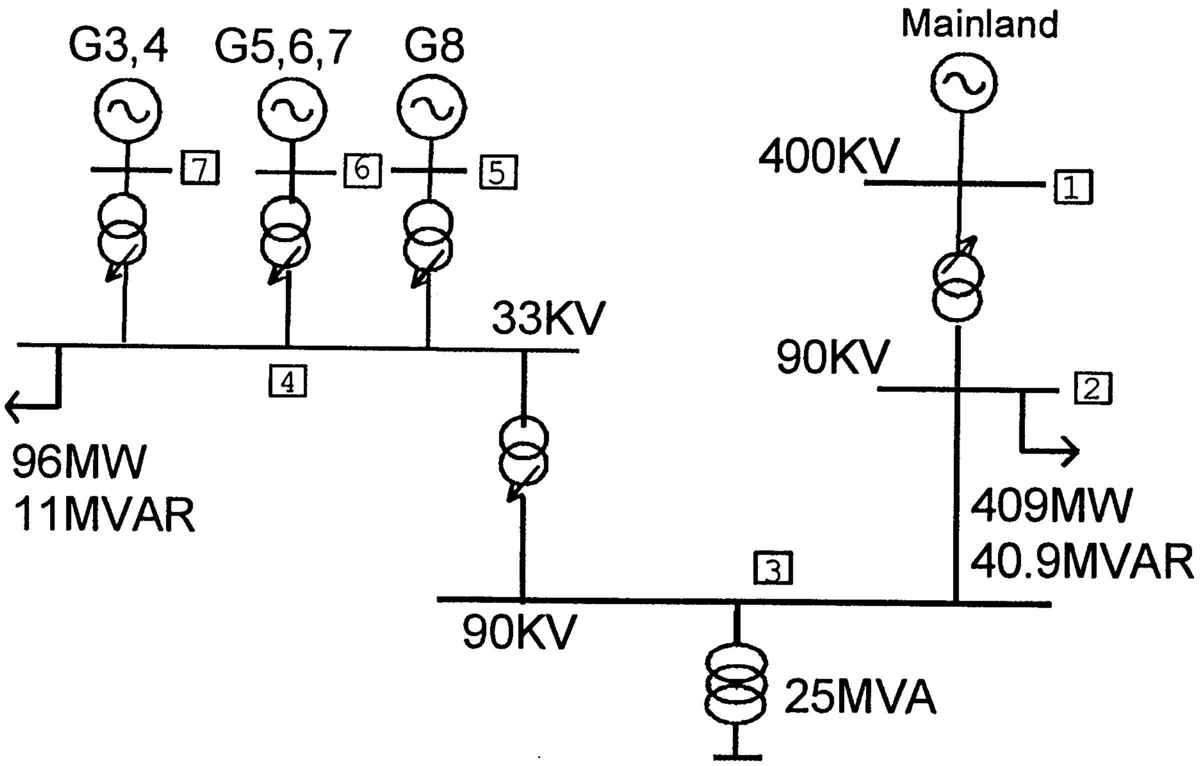
Table 1 Bus data for IEEE 14 Bus System

BUS RESULTS:
IEEE 14 BUS DATA AS FROM GLOVER FILE

NO.	V	DELTA	PG	QG	PL	QL	
1	1.060	0.000	2.323	-0.163	0.000	0.000	*
2	1.045	-4.956	0.400	0.412	0.217	0.127	
3	1.010	-12.702	0.000	0.234	0.942	0.190	
4	1.018	-10.313	0.000	0.000	0.478	-0.039	
5	1.020	-8.761	0.000	0.000	0.076	0.016	
6	1.070	-14.834	0.000	0.148	0.112	0.075	*
7	1.061	-13.631	0.000	0.000	0.000	0.000	*
8	1.090	-13.631	0.000	0.178	0.000	0.000	*
9	1.055	-15.281	0.000	0.000	0.295	-0.024	*
10	1.050	-15.487	0.000	0.000	0.090	0.058	*
11	1.056	-15.287	0.000	0.000	0.035	0.018	*
12	1.055	-15.670	0.000	0.000	0.061	0.016	*
13	1.050	-15.728	0.000	0.000	0.135	0.058	*
14	1.035	-16.473	0.000	0.000	0.149	0.050	
		TOTAL:	2.723	0.809	2.590	0.545	

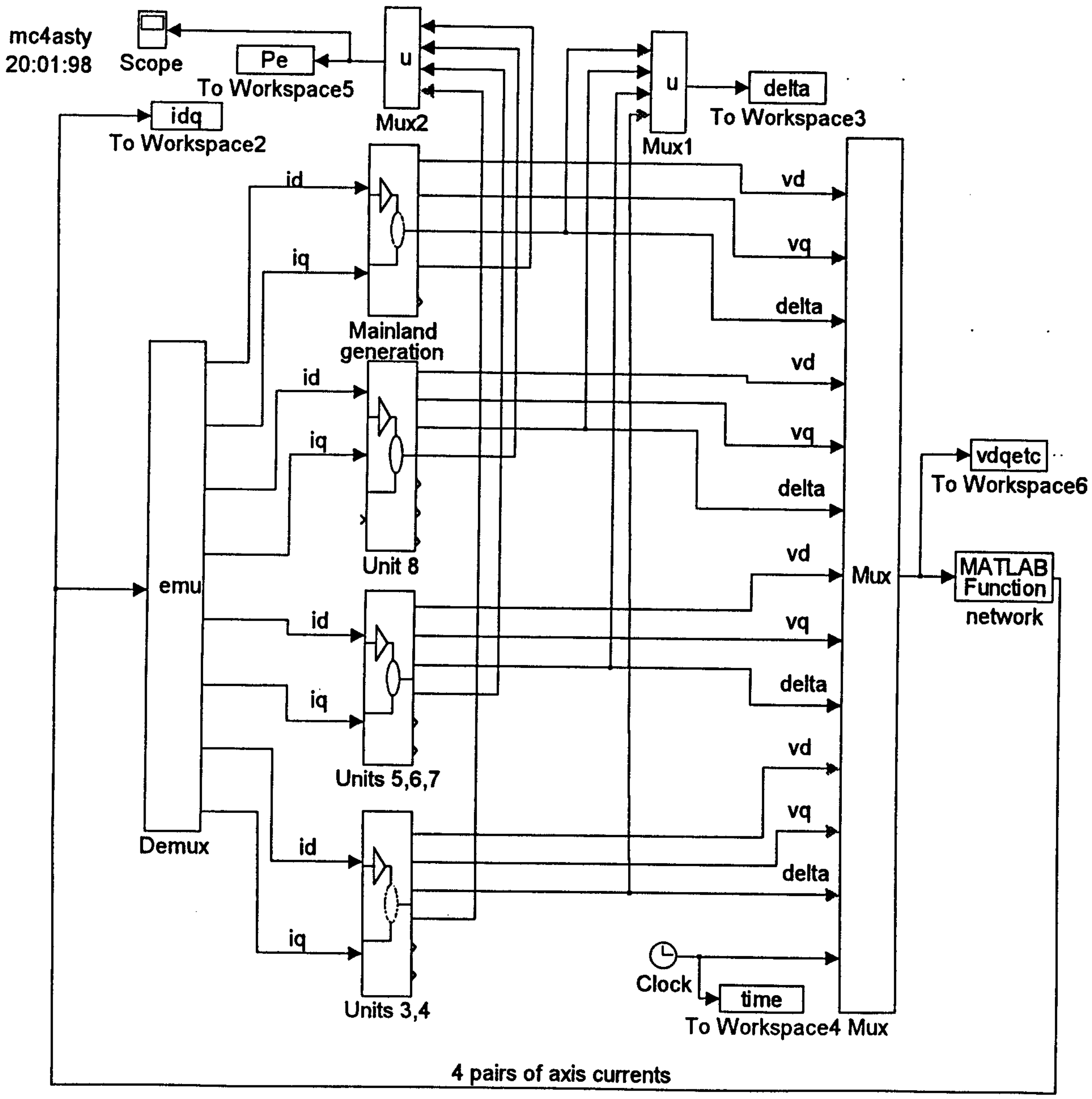
*--V OUTSIDE RANGE 0.95 TO 1.05; #--REACTIVE POWER LIMIT IMPOSED

Table 2 Bus Results for IEEE 14 Bus System



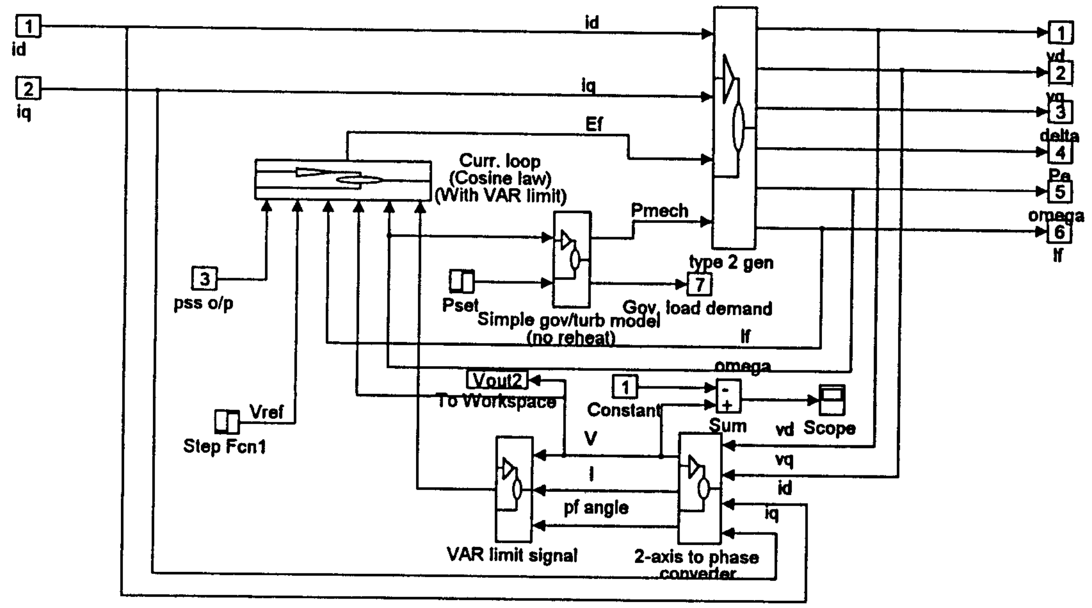
Island 4 Machine Power System

Figure 1



Island 4 machine system

Figure 2



Island unit 8 turbo-generator with full excitation converter including var limiter

Figure 3

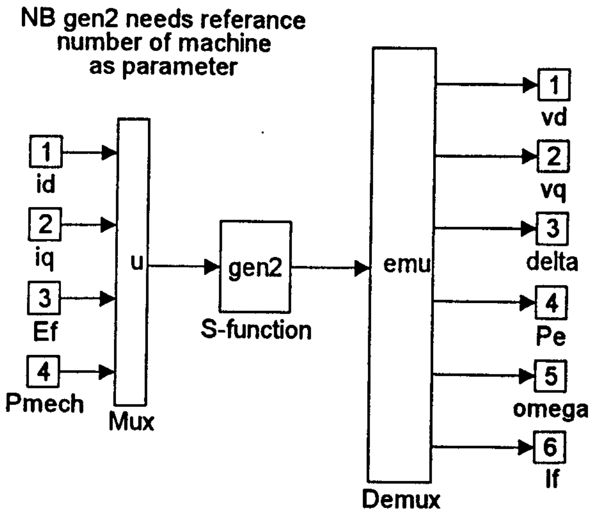


Figure 4

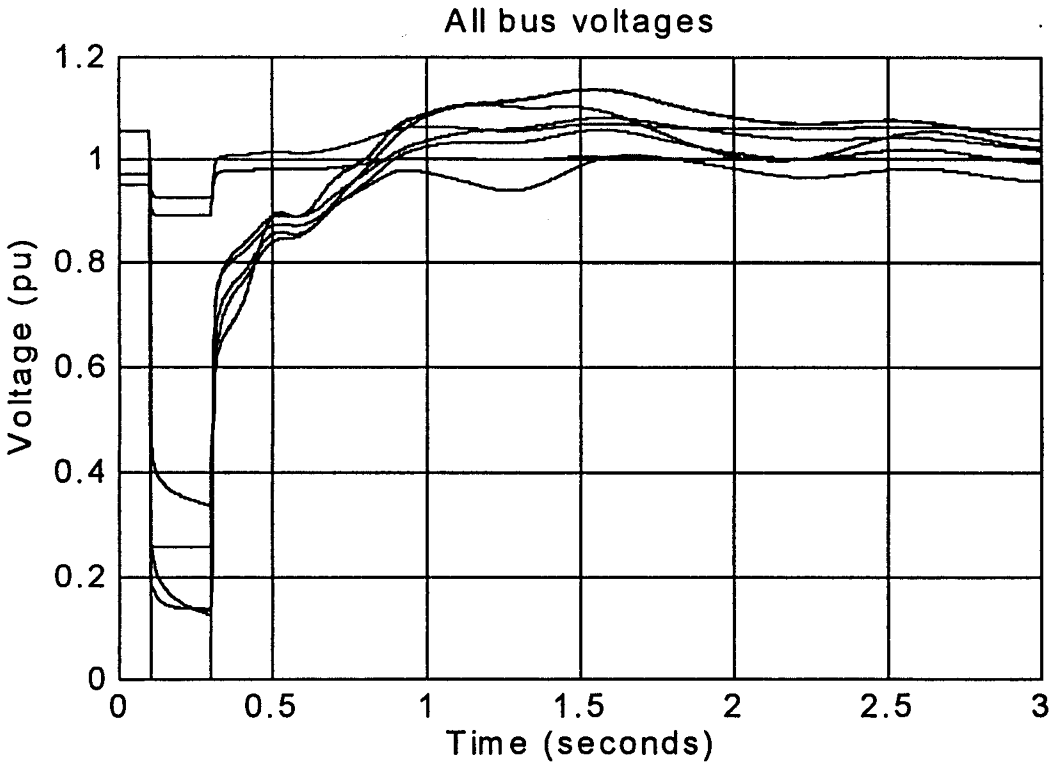


Figure 5

Machines 2-4 type 2 (transient/sub-transient saliency)
With excitation system and prime mover models
but no PSS
(mc4apsty.m & linear.m; K2P=0)

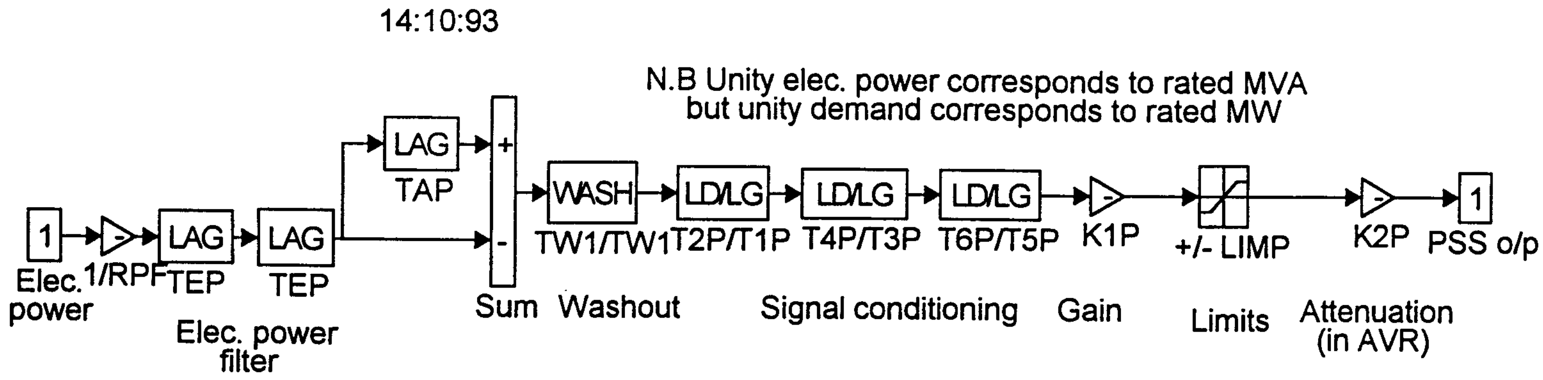
Frequency (Hz)	Damping Factor	Mode
2.327	0.222	4 against 3
1.278	0.0909	3/4 against 2
0.6531	0.1546	2/3/4 against 1

Machines 2-4 type 2
With excitation system and prime mover models
and PSS*
(mc4apsty.m & linear.m; K2P=0.076)

Frequency (Hz)	Damping Factor	Mode
2.33	0.2188	4 against 3
1.182	0.0784	3/4 against 2
0.4587	0.5624	2/3/4 against 1

* the PSS was not tuned - simply copied from that used for another generator!

Table 3 Load angle oscillation mode eigenvalue results



PSS TYPE 2 — ELECTRIC POWER ONLY (BASED ON CB 105 MW)

Figure 6