SIMPLIFIED 14-GENERATOR MODEL OF THE SE AUSTRALIAN POWER SYSTEM

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Revision 3

Preface to Revision 3

In order to provide practical and realistic data two sets of system parameters have been corrected from those listed in Revision 2. They are:

- In Table 10 the series impedance of the three lines 405 to 409 have been changed from 0.018+j0.0122 to 0.018+j0.122 pu
- In Table 11 there are three transformers, each rated 750 MVA, reactance 6% on rating (0.8% on 100 MVA) between buses 413-414. The correct values are listed in the Table; the loadflow files have been corrected accordingly.

As to be expected, the PVr characteristics of the generators as well as the PSS transfer functions determined in Revision 2 remain unchanged.

As a consequence:

- A new set of system load flow files have been provided, together with the revised Matlab files for Cases 1 and 6.
- The results listed in Table 8 and Table 9 covering the outputs of generators and SVCs, respectively, have been modified.

Note: The results of the analysis in Revision 2, based on the system data employed in that revision, are in themselves correct and unchanged.

1 Introduction

The purpose of this document is to provide a test system which can be used as a test bed for the small-signal analysis and design of power system stabilisers (PSSs) and other controllers *in a multi-machine power system*.

Frequently papers are published in which the performance of PSSs designed using ‘advanced’ methods is compared to that of PSSs designed using so-called ‘conventional’ techniques. More often than not, the latter design does not represent a properly-designed ‘conventional’ PSS. In the following a basis for such a ‘conventional’ PSS design is outlined and its performance demonstrated. It is used in practice by a number of organisations.

An important aspect of the design of PSSs for use on practical systems is that PSSs should contribute to the damping of inter-area, local-area and intra-station modes. This aspect is seldom tested adequately in most ‘advanced’ design methods because:

- a single-machine infinite-bus test system is typically employed by the proponent; it does not reveal the damping performance of the proposed PSS over the full range of modal frequencies likely to be encountered in practice, i.e. from the low frequency inter-area modes (~1.5 rad/s) to the higher local / intra-station frequencies (12+ rad/s);

- the contributions to modal damping by the proposed PSS are not validated over a wide range of operating conditions encountered in practice, light to peak load, for normal and contingency operation, etc.;

- the models of AVR/excitation systems employed in the proponent’s system are often very simple. In practice such models may be third or higher order.

For designs of advanced PSSs to be credible for practical application, the proponents should demonstrate the above issues have been adequately addressed. An aim of the 14-generator test system is to provide researchers and developers with a system possessing the features highlighted above, i.e. a range of modal frequencies, a range of operating conditions, and higher-order air/excitation system models.

The generators in the 14-machine system are in fact equivalent generators each representing a power station (PS) of 2 to 12 units. While the generators in each station could have been individually represented, this adds an additional level of complexity and increases system size, moreover, it is not warranted for the primary purpose of this document.

Included in Appendix I is a complete set of data that allows an interested party (i) to replicate the results provided using that party’s loadflow and small-signal dynamics analysis packages, (ii) to cross-check results obtained by the party with those presented here, (iii) to insert in a Matlab environment the party’s own controller, etc., into the power system for the analysis being conducted for research purposes.

2 Caveats

The model of the power system used in this document is *loosely* based on the southern and eastern Australian networks. Therefore,

- it does not accurately represent any particular aspect of those networks;
- the model should not be used to draw any conclusions relating to the actual performance of the networks comprising the southern and eastern Australian grid, either for any normal or any hypothetical contingency condition;
- the model is suitable for educational purposes / research-oriented analysis only.

3 Information provided

The following data are provided:

- The load flow data and results files in PSS/E format together with the associated data tables for six normal operating conditions. These cover peak, medium and light load conditions with various inter-area power transfers and directions of flow.
- Tables of the parameters for the generators, SVCs, excitation systems and PSSs for use in the small-signal analysis of the dynamic performance of the system.
- The P-Vr frequency response characteristics of the generators over the range of operating conditions. These are presented in graphical form (on machine base).
- Tables of the rotor modes of oscillation for the six cases with PSSs in- and out-of-service.
- Matlab *.mat files of the ABCD parameters, eigenvalues, eigenvectors and participation factors for two of the six cases with the PSSs both in- and out-of-service.

4 The Simplified System

The simplified 14-generator, 50 Hz system is shown in Fig. 1. It represents a long, linear system as opposed to the more tightly meshed networks found in Europe and the USA. For convenience, it has been divided into 5 areas in which areas 1 and 2 are more closely coupled electrically. There are in essence 4 main areas and hence 3 inter-area modes, as well as 10 local-area modes. Without PSSs many of these modes are unstable.

In order to tune generator PSSs in practice a wide range of normal operating conditions and contingencies are considered. In the data provided in the Appendix, however, only six normal conditions are used for illustrative purposes. The operating conditions, system loads and major inter-area flows are listed in Table 1.

Table 1 Six normal steady-state operating conditions

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Load Condition	Heavy	Medium-heavy	Peak	Light	Medium	Light
Total generation (MW)	23030	21590	25430	15050	19060	14840
Total load (MW)	22300	21000	24800	14810	18600	14630

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Inter-area flows	(North to south)	(South to north)	(Hydro to N & S)	(Area 2 to N & S)	(N & S to pumping)	(~Zero transfers)
Area 4 to Area 2 (MW)	500	-500	-500	-200	300	0
Area 2 to Area 1 (MW)	1134	-1120	-1525	470	740	270
Area 1 to Area 3 (MW)	1000	-1000	1000	200	-200	0
Area 3 to Area 5 (MW)	500	-500	250	200	250	0

The schedules of generation for the six cases are listed in Appendix I, Table 8. Note that the number of generating units on-line in certain power stations (designated *PS_#, e.g. HPS_1) can vary considerably over the range of operating conditions.

5 Loadflow analysis

Data for the loadflow analysis of the six normal operating conditions given in Table 1 is supplied in Appendix I.1. Included in Appendix I.1 are relevant results of the analysis such as reactive outputs of generators and SVCs, together with tap positions on generator and network transformers. This information permits the loadflows to be set up on any loadflow platform and the results checked against those provided in this document.

The loadflow data is also provided in Siemens-PTI PSS/E version 29 format. These files for the six operating conditions for use with PSS/E are accessible from the web site in [1].

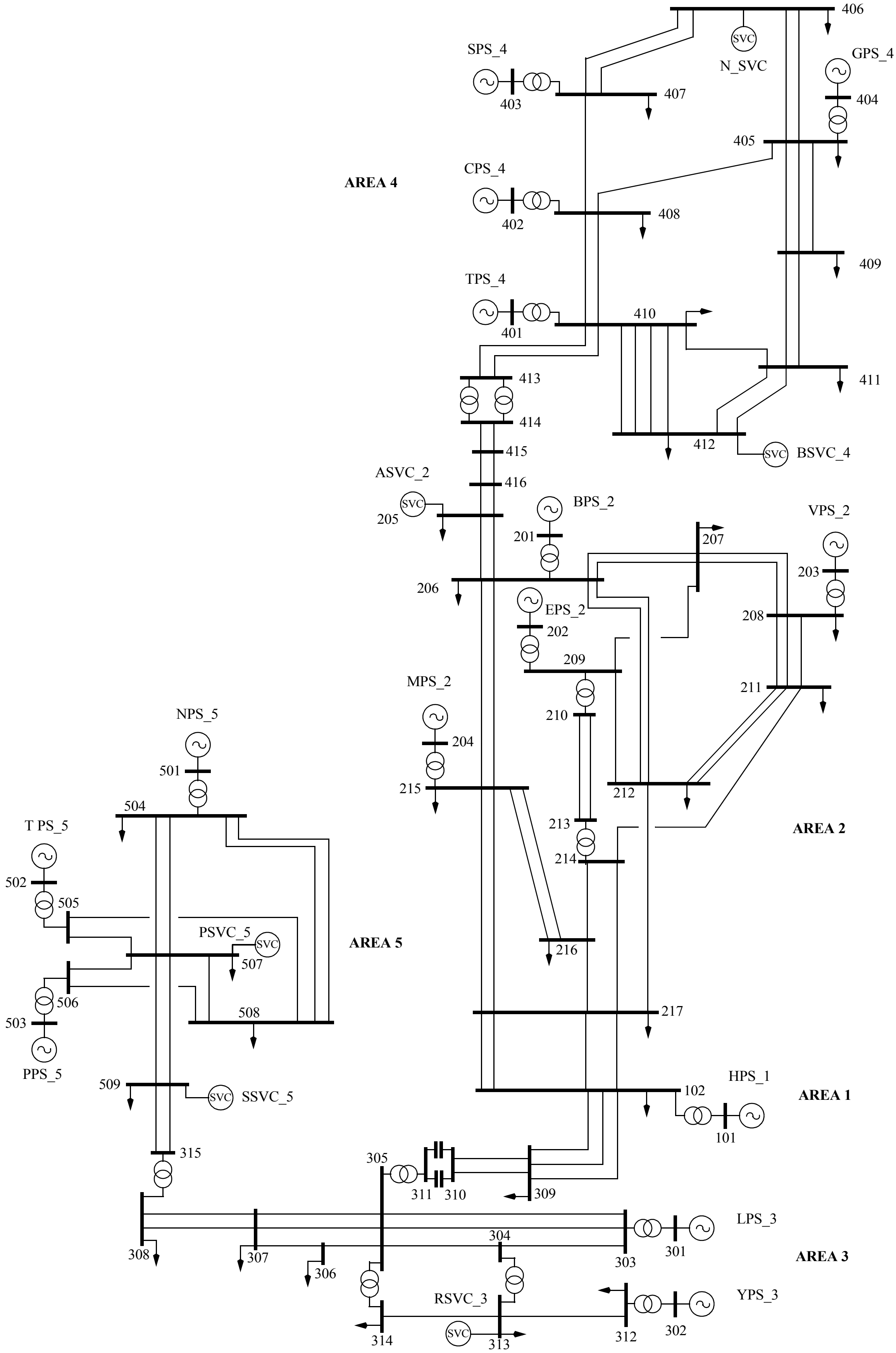


Figure 1 Simplified 14-generator, 50 Hz system.

6 Design of PSSs based on the P-Vr Method for multi-machine systems

6.1 Introduction

Comparisons between conventional PSS design methods such as the 'GEP', 'P-Vr' - and a method based on residues - for multi-machine power systems are discussed in [7] and [11]. A comparison of the P-Vr and GEP methods and their features are provided in Table 23 of Appendix I.4.

6.2 Concepts based on an ideal PSS

Consider the idealised shaft dynamics of the simplified generator model shown in Fig. 2. Assume that a feedback loop can be added from the rotor speed signal $\Delta\omega$ to the torque signal ΔP_d - as shown in Fig. 2 - such that $\Delta P_{ds} = k\Delta\omega$. It is clear that increasing the gain *k* has the same effect as increasing the *inherent damping torque coefficient* k_d [13], that is, enhancing the damping of rotor oscillations. The block with gain *k* represents an ideal PSS that induces on the rotor a torque of electro-magnetic origin proportional to speed perturbations. The gain *k*, like k_d, is a *damping torque coefficient* which we call the *damping gain* of the PSS. (The difference between the latter gain and the conventional 'PSS gain' is discussed shortly.) The gaol in the design of a practical PSS is to achieve the same result, the damping gain being adjusted to meet the specifications on the damping for the rotor modes of oscillation. Framed in this context, the damping gain *k* of a practical PSS expressed in per unit on machine base becomes a meaningful quantity.

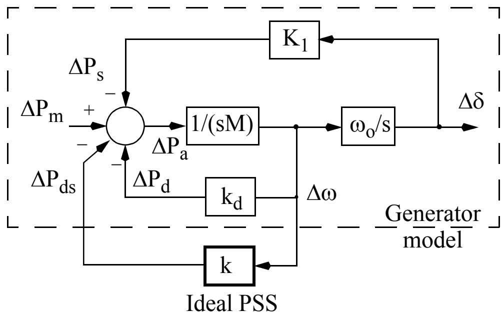


Figure 2 The ideal PSS, represented by a damping gain *k*, introduces a pure damping torque on the rotor of a simplified generator model.

6.3 Theoretical background

The design of the compensating transfer function (TF) for the PSS of generator *i* in a multi-machine power system is based on the so-called P-Vr TF of generator *i*. This is the TF from the AVR voltage reference input, 'Vr', on generator *i* to the torque of electromagnetic origin (or electrical power output, 'P') on that generator, calculated with the shaft dynamics of *all* machines disabled [2], [3]. In the following, $\Delta V_{ri}(s)$ and $\Delta P_{ei}(s)$ are perturbations in the reference voltage and the electrical torque, respectively. (For small disturbances the per-unit perturbations in electrical power and electrical torque are identical.)

The frequency response of the P-Vr TF, $H_{PVri}(s) = \Delta P_{ei}(s)/\Delta V_{ri}(s)$, is easily calculated. To disable the shaft dynamics of all machines the rows and/or columns of all generator speed states are eliminated in the ABCD matrices of the linearized state equations of the system. The frequency response(s) $\Delta P_{ei}(j\omega_f)/\Delta V_{ri}(j\omega_f)$ are then calculated over the range of rotor modal frequencies (typically 1.5 to 12 rad/s).

The TF $H_{PSSi}(s)$ of a PSS is typically of the form $k_i G_i(s)$. When the transfer functions of the PSS compensation block $G_{ci}(s)$, and the wash-out and low-pass filters, $G_{Wi}(s)$ and $G_{LPi}(s)$ respectively, are added the PSS TF takes the form,

$$H_{PSSi}(s) = k_i G_i(s) = k_i G_{ci}(s) \cdot G_{Wi}(s) \cdot G_{LPi}(s). \tag{1}$$

Alternatively, considering the typical forms of the relevant TFs, the PSS TF is

$$H_{PSSi}(s) = k_i G_i(s) = k_i \cdot \left[\frac{sT_W}{1 + sT_W} \cdot \frac{1}{k_c} \cdot \frac{(1 + c_1 s + c_2 s^2)(1 + sT_{a1})\ldots}{(1 + sT_{b1})\ldots(1 + sT_1)(1 + sT_2)\ldots} \right] \tag{2}$$

where, for generator *i*, T_W is the time constant of the washout filter; k_c, c_1, c_2, T_{a1}, …, T_{b1}, … are the parameters of the compensation TF $G_{ci}(s)$ determined in the design procedure described below, and T_1, T_2, … are the time constants of the low-pass filter. The corner frequencies of the washout and low-pass filters are selected such that the phase shifts introduced at the frequencies of the rotor modes are negligible. The PSS TF must be proper.

Note that, in the context of (2), the gain k_i has been referred to as the '*damping gain*' of the PSS. If the washout filter is ignored the 'dc' gain of the PSS TF is k_i/k_c; *conventionally this is referred to as the 'PSS Gain'*. However, the PSS gain k_i/k_c has little meaning as k_c is machine and system dependent.

The compensation TF $G_{ci}(s)$ is designed to achieve the desired *left-shift* in the relevant modes of rotor oscillation. The damping gain k_i (on machine base) of the PSS determines the *extent* of the left-shift. The aim of the design procedure is to introduce on the generator shaft a damping torque (a torque proportional to machine speed); this causes the modes of rotor oscillation to be shifted to the left in the *s*-plane. Thus the ideal TF between speed $\Delta\omega_i$ and the electrical damping torque perturbations ΔP_{ei} due to the PSS over the range of complex frequencies of the rotor modes should be

$$D_{ei} = \Delta P_{ei}(s)/\Delta\omega_i(s)\big|_{PSSi}, \tag{3}$$

where D_{ei} is a damping torque coefficient (e.g. as is *k* in Fig. 2) and - for design purposes - is a real number (p.u. on machine base). The TF $G_{ci}(s)$ compensates in *magnitude as well as* *phase* for the P-Vr TF $H_{PVri}(s)$ of machine i. With rotor speed being used as the input signal to the PSS, whose output is $\Delta V_{si}(s)$, the expression (3) for D_{ei} can be written:

$$D_{ei} = \frac{\Delta P_{ei}(s)}{\Delta V_{si}(s)} \cdot \frac{\Delta V_{si}(s)}{\Delta \omega_i(s)} = H_{PVri}(s)[k_i G_{ci}(s)]; \tag{4}$$

hence, rearranging (4), we find

$$[k_i G_{ci}(s)] = D_{ei}/(H_{PVri}(s)). \tag{5}$$

It follows from an examination of (5) that $k_i = D_{ei}$ and $G_{ci}(s) = 1/(H_{PVri}(s))$. As in the case of the simplified generator model of Fig. 2, the gain k_i of the PSS can thus also be considered to be a damping torque coefficient. The practical, proper TF for the i-th PSS is that of (2), i.e.:

$$[k_i G_i(s)] = k_i\{1/(PVR_i(s))\}\{\text{washout \& low-pass filters}\}$$

where $PVR_i(s)$ is the *synthesized form* of P-Vr characteristic, $H_{PVri}(s)$. As most rotor modes are relatively lightly damped, s can be replaced by $j\omega_f$ and conventional frequency response methods can be employed in the design procedure. In practice, the aim of a design is to ensure that, over the range of frequencies of rotor oscillations, the magnitude response of the RHS of (3) is flat with zero or slightly lagging phase shift. This means that the PSS introduces an almost pure damping torque over the frequency range of the rotor modes. Because of the more-or-less invariant nature of the TF $H_{PVri}(s)$ over a wide range of operating conditions, fixed-parameter PSSs tend to be robust [5].

Note that speed appears to be the ideal stabilizing signal because the damping torque induced on the shaft of the generator by the associated PSS is related to speed through a simple gain. Moreover, this gain being a damping torque coefficient has practical significance, e.g. a damping gain k_i of 20 pu on machine rating can typically be considered a moderate gain setting for a speed-PSS. A practical form of the “speed-PSS” is the “Integral-of-accelerating-power PSS” for which the design procedure outlined above is applicable.

The approach to the design of speed-PSSs can be adapted to the design of power-input PSSs. If the perturbations in mechanical power are negligible over the frequency range of interest the equation of motion of the unit’s shaft can be written $\Delta\omega(s) = -\Delta P_{ei}(s)/(2Hs)$ [13]; $\Delta\omega$ is then the input to the speed-PSS.

7 The P-Vr characteristics of the 14 generators and the associated synthesized characteristics

For each of the generators the P-Vr characteristics are determined for the six loadflow cases as shown in Fig. 3 to Fig. 16. These characteristics were calculated using a software package for the analysis of the small-signal dynamic performance and control of large power systems [14].

It should be noted in this analysis that the operating conditions on which the load flows, and therefore the P-Vr characteristics, are based are normal operating conditions. In practice, the

P-Vr characteristics for a relevant set of contingency conditions are also considered when determining the synthesized characteristic.

The synthesized P-Vr characteristic for each generator is derived based on the following:

- The modal frequency range of interest is 1.5 to 12 rad/s.

- The synthesized characteristic is a best fit of the P-Vr characteristics for the range of cases examined over the modal frequency range 1.5 to 12 rad/s. The 'best fit' characteristic is considered to be that characteristic which lies in the middle of the magnitude and phase bands formed by the P-Vr characteristics. If particular P-Vr characteristics tend lie outside the bands formed by the majority of the characteristics, the synthesized P-Vr is offset towards the band formed by the majority (e.g. see Fig. 12).

- Less phase lead at the inter-area model frequencies may be required than that provided by the synthesized TF based on P-Vr characteristic [11]. It can be accommodated by a gain-lag-lead transfer function block or by adjusting the synthesized transfer function at the inter-area frequencies. This feature has the effect of increasing the damping of the inter-area modes, however, it is not incorporated in following analysis.

The P-Vr characteristics for the 14 generators, shown in Fig. 3 to Fig. 16, are in per unit on the machine rating given in Table 8.

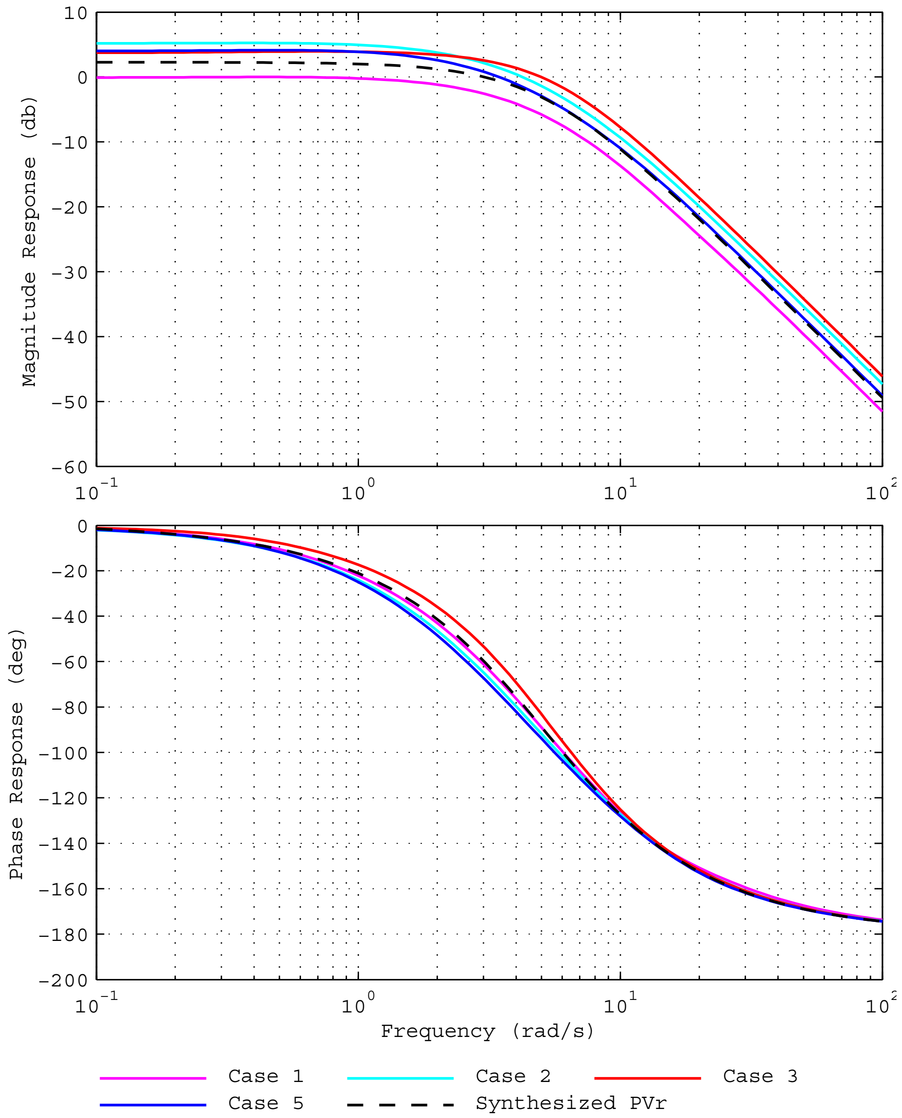


Figure 3 P-Vr characteristics, calculated and synthesized ($PVR(s)$), for generator HPS_1. (In cases 4 & 6 the PSS is switched off as it is operating as a synchronous compensator.)

$$PVR(s) = 1.3/(1 + s0.373 + s^2 0.0385)$$

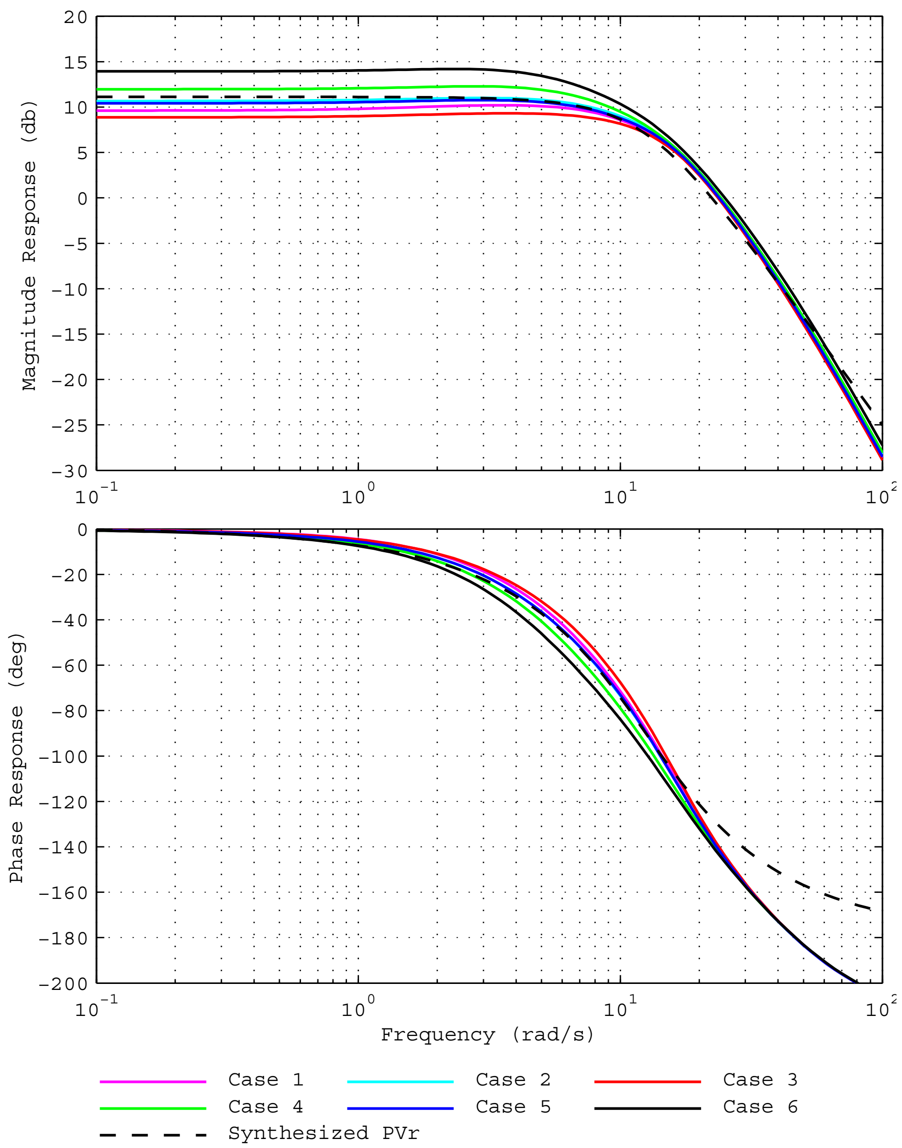


Figure 4 P-Vr characteristics, calculated and synthesized ($PVR(s)$), for generator BPS_2.

$$PVR(s) = 3.6/(1 + s0.128 + s^2 0.0064)$$

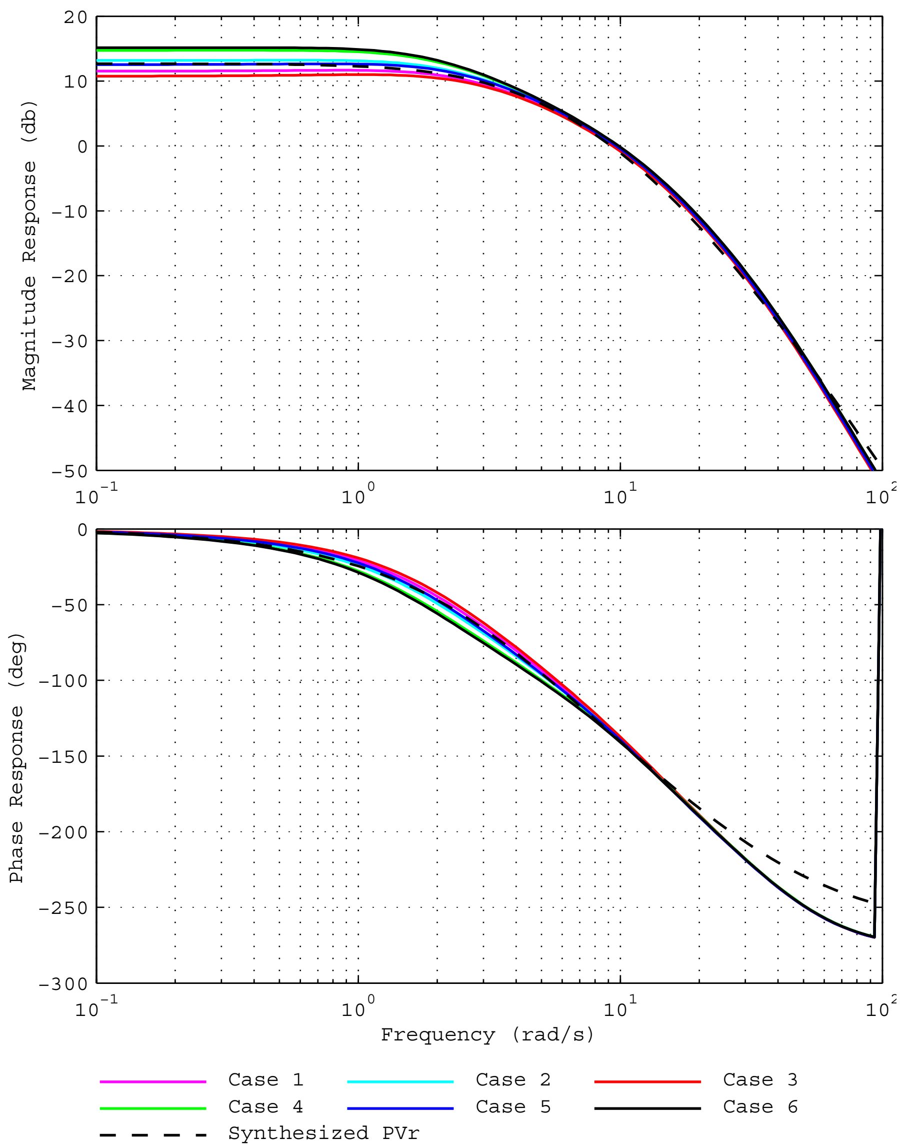


Figure 5 P-Vr characteristics, calculated and synthesized $(PVR(s))$, for generator EPS_2.

$$PVR(s) = 4.3/[(1 + s0.286)(1 + s0.111)(1 + s0.040)]$$

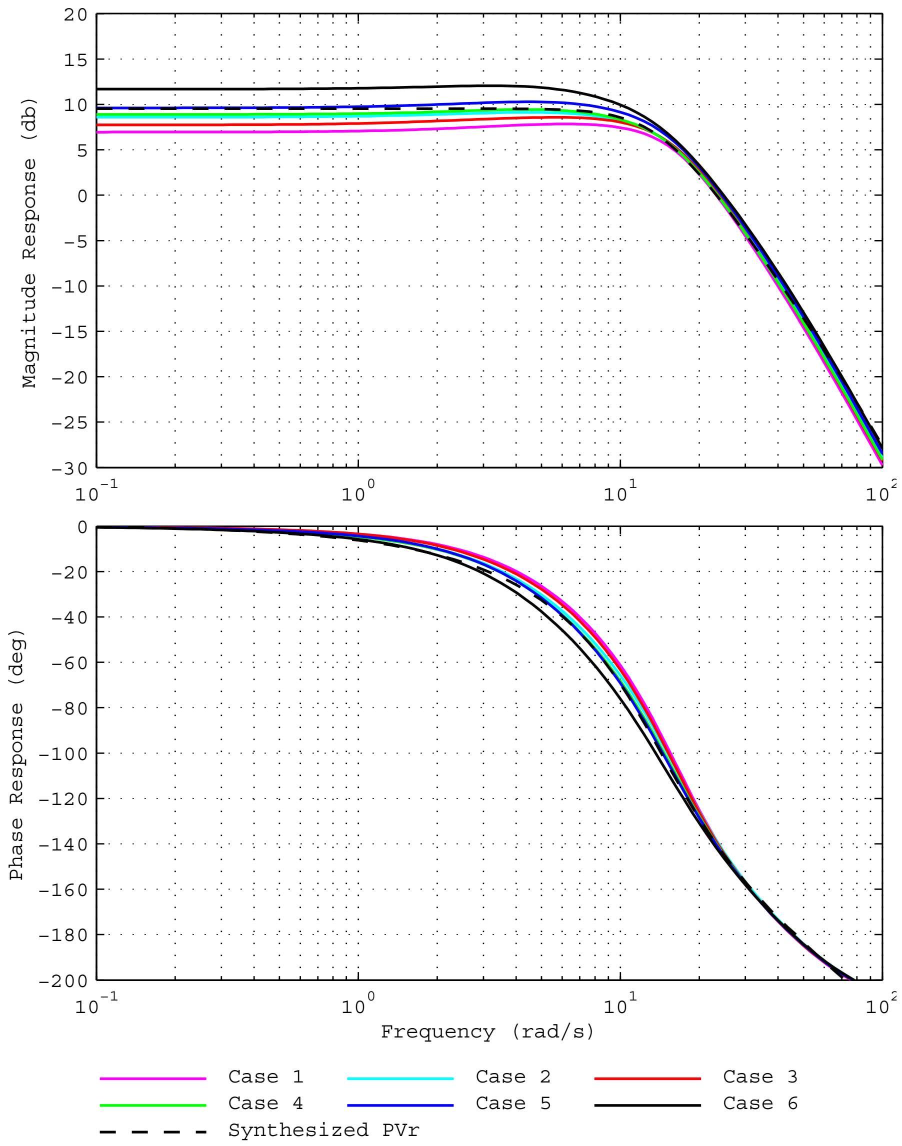


Figure 6 P-Vr characteristics, calculated and synthesized ($PVR(s)$), for generator MPS_2.

$$PVR(s) = 3.0/[(1 + s0.01)(1 + s0.1 + s^2 0.0051)]$$

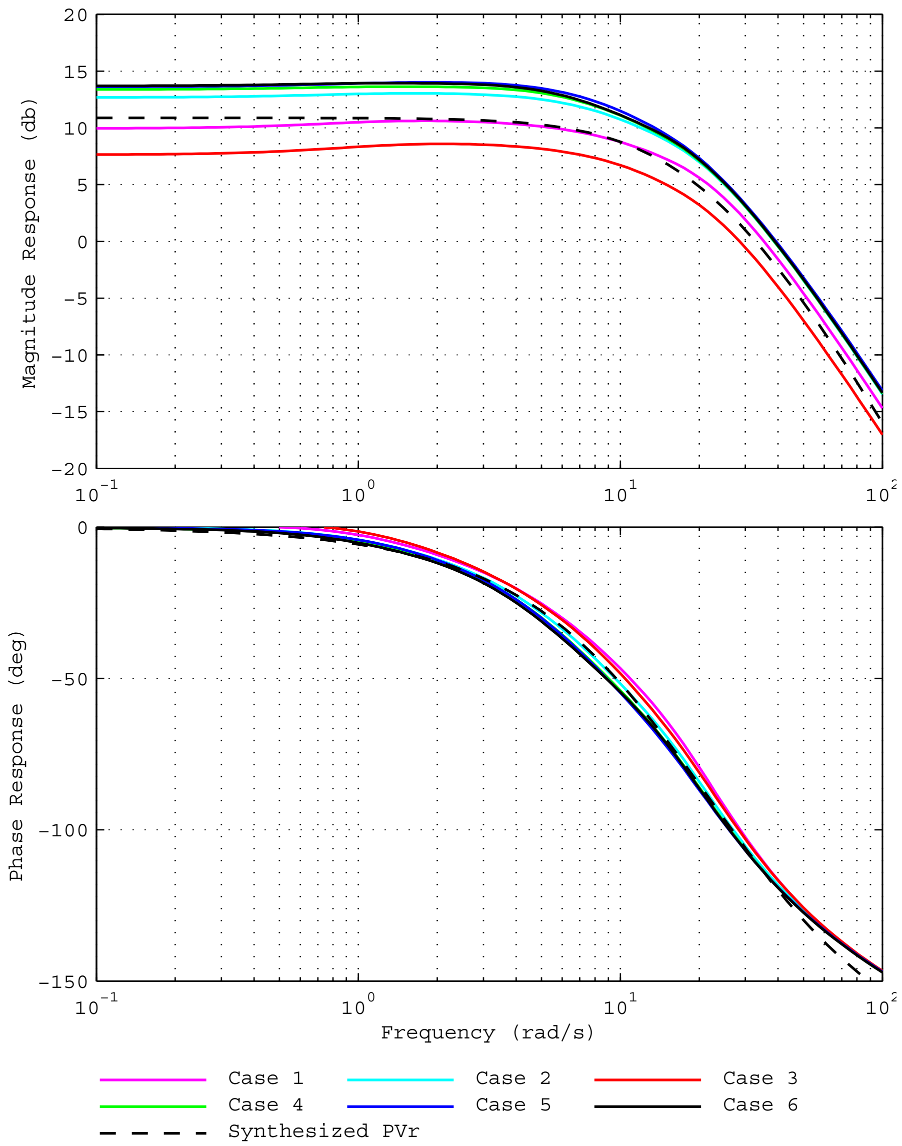


Figure 7 P-Vr characteristics, calculated and synthesized $(PVR(s))$, for generator VPS_2.

$$PVR(s) = 3.5/[(1 + s0.0292)(1 + s0.0708)]$$

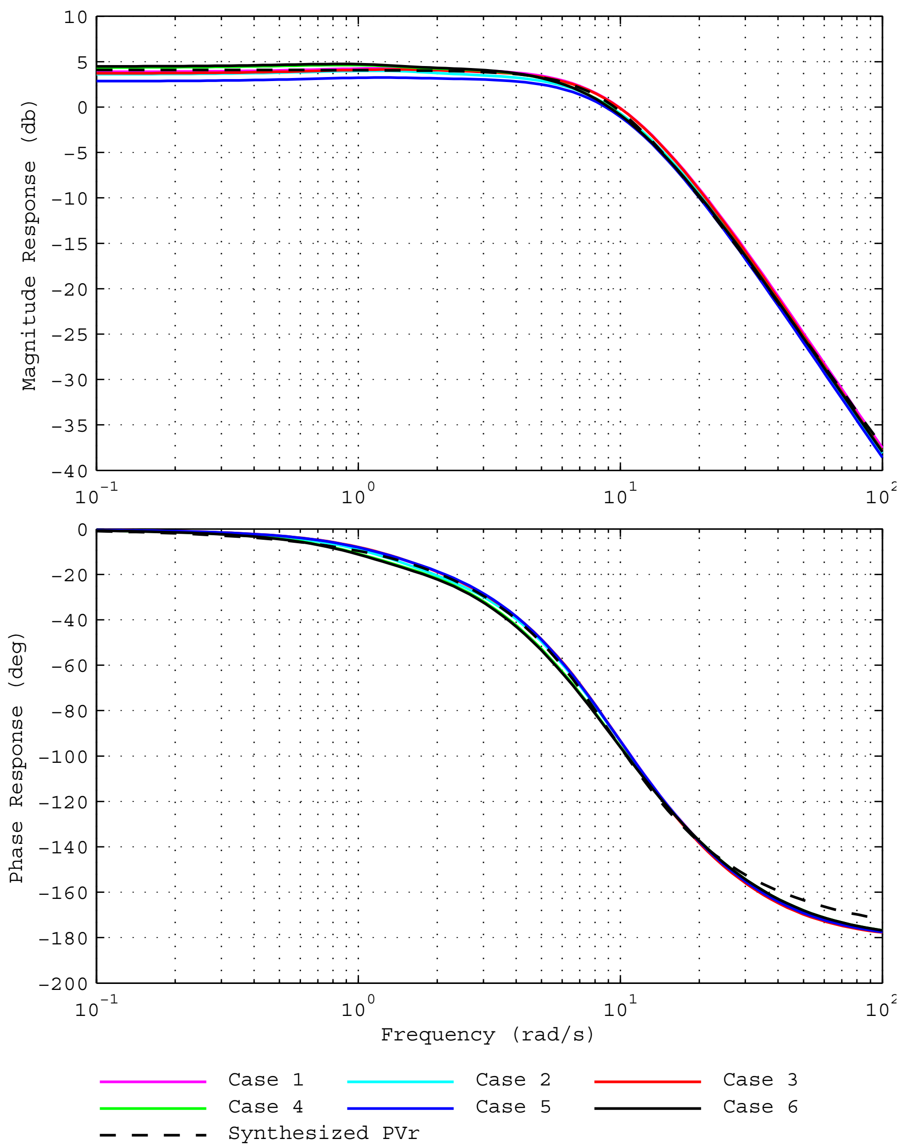


Figure 8 P-Vr characteristics, calculated and synthesized ($PVR(s)$), for generator LPS_3.

$$PVR(s) = 1.6/(1 + s0.168 + s^2 0.0118)$$

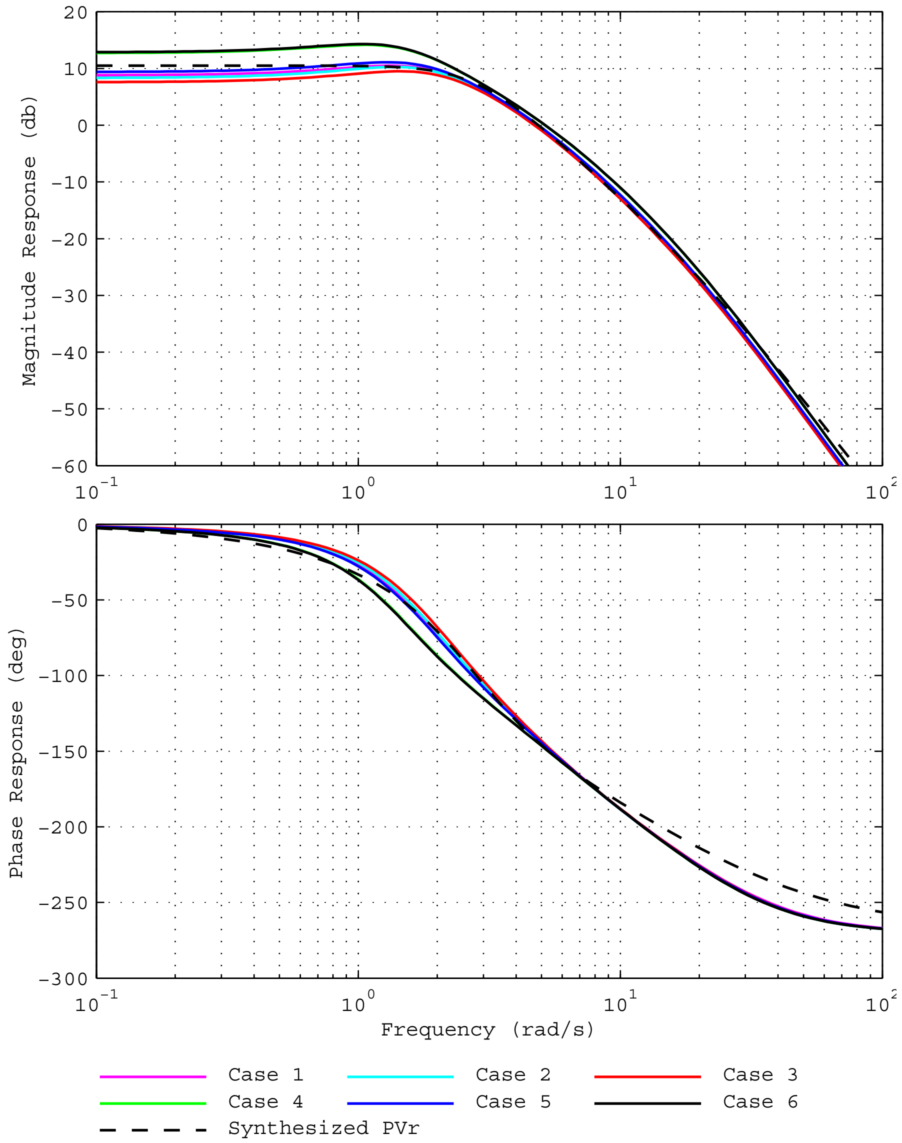


Figure 9 P-Vr characteristics, calculated and synthesized $(PVR(s))$, for generator YPS_3

$$PVR(s) = 3.35/[(1 + s0.05)(1 + s0.509 + s^2 0.132)]$$

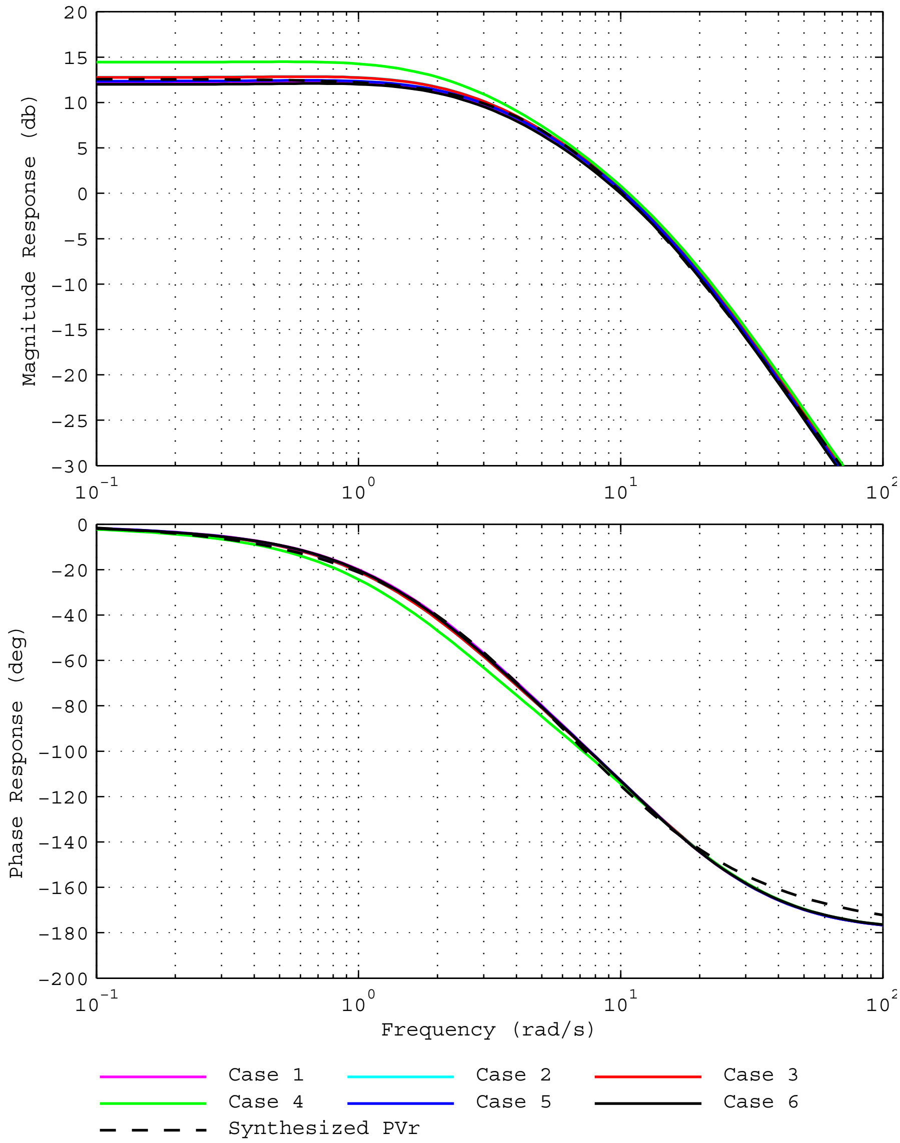


Figure 10 P-Vr characteristics, calculated and synthesized ($PVR(s)$), for generator CPS_4.

$$PVR(s) = 4.25/[(1 + s0.278)(1 + s0.100)]$$

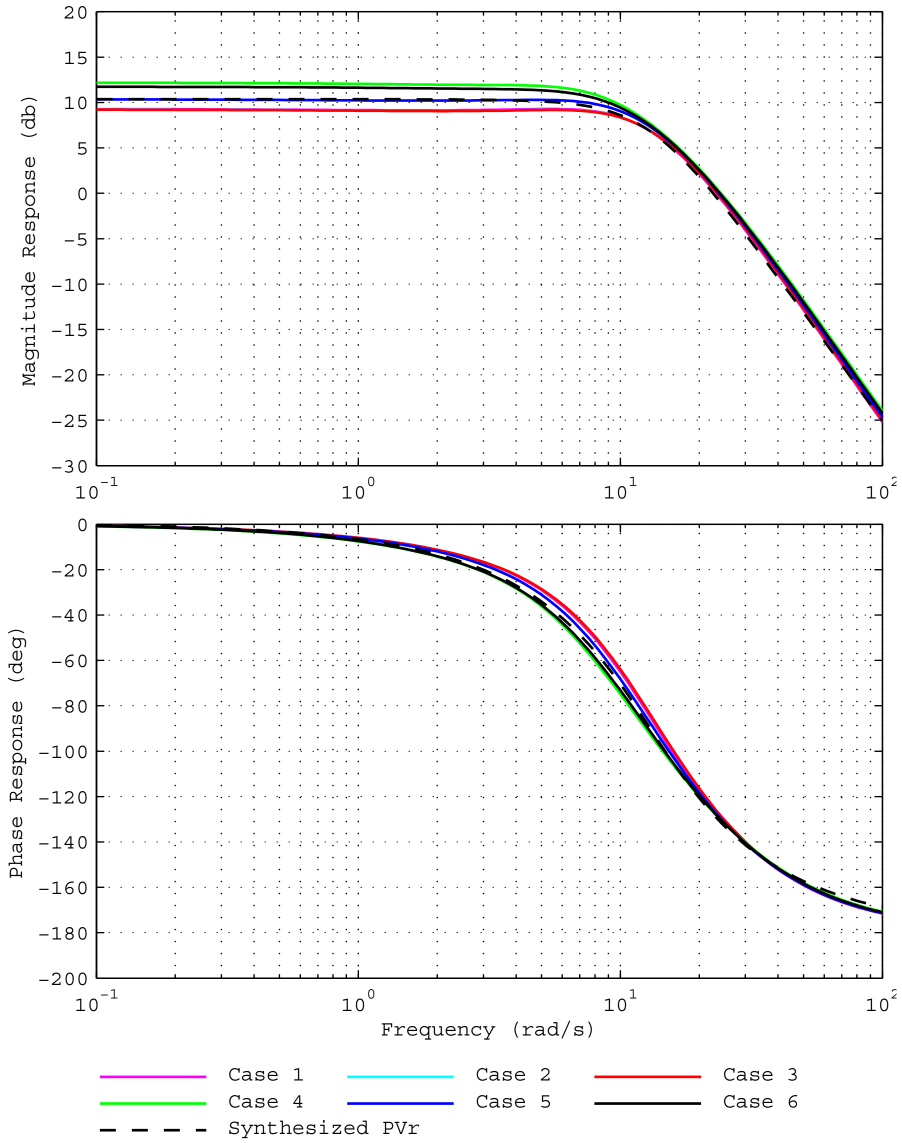


Figure 11 P-Vr characteristics, calculated and synthesized ($PVR(s)$), for generator GPS_4.

$$PVR(s) = 3.3/(1 + s0.115 + s^2 0.00592)$$

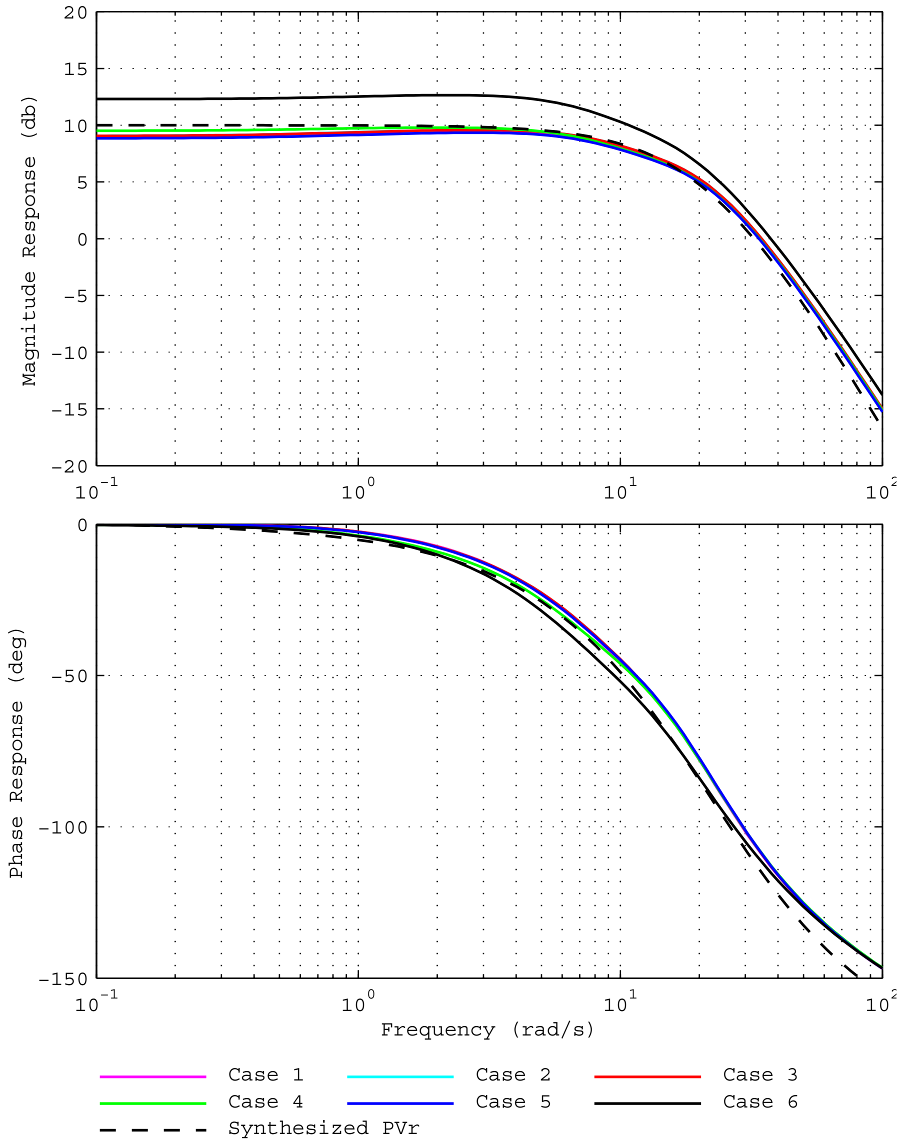


Figure 12 P-Vr characteristics, calculated and synthesized ($PVR(s)$), for generator SPS_4. The synthesized P-Vr characteristic is weighted towards those of Cases 1 to 5.

$$PVR(s) = 3.16/(1 + s0.0909 + s^2 0.00207)$$

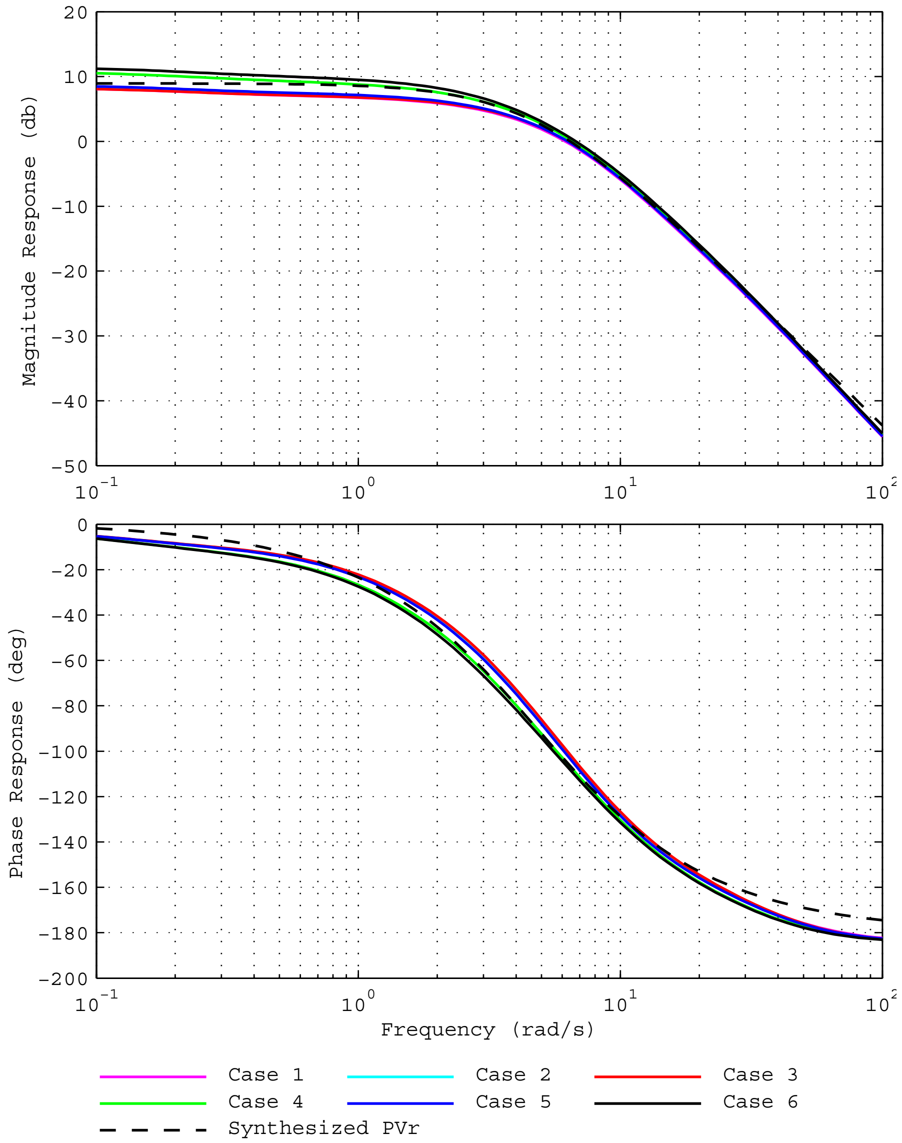


Figure 13 P-Vr characteristics, calculated and synthesized ($PVR(s)$), for generator TPS_4.

$$PVR(s) = 2.8/[(1+s0.208)(1+s0.208)]$$

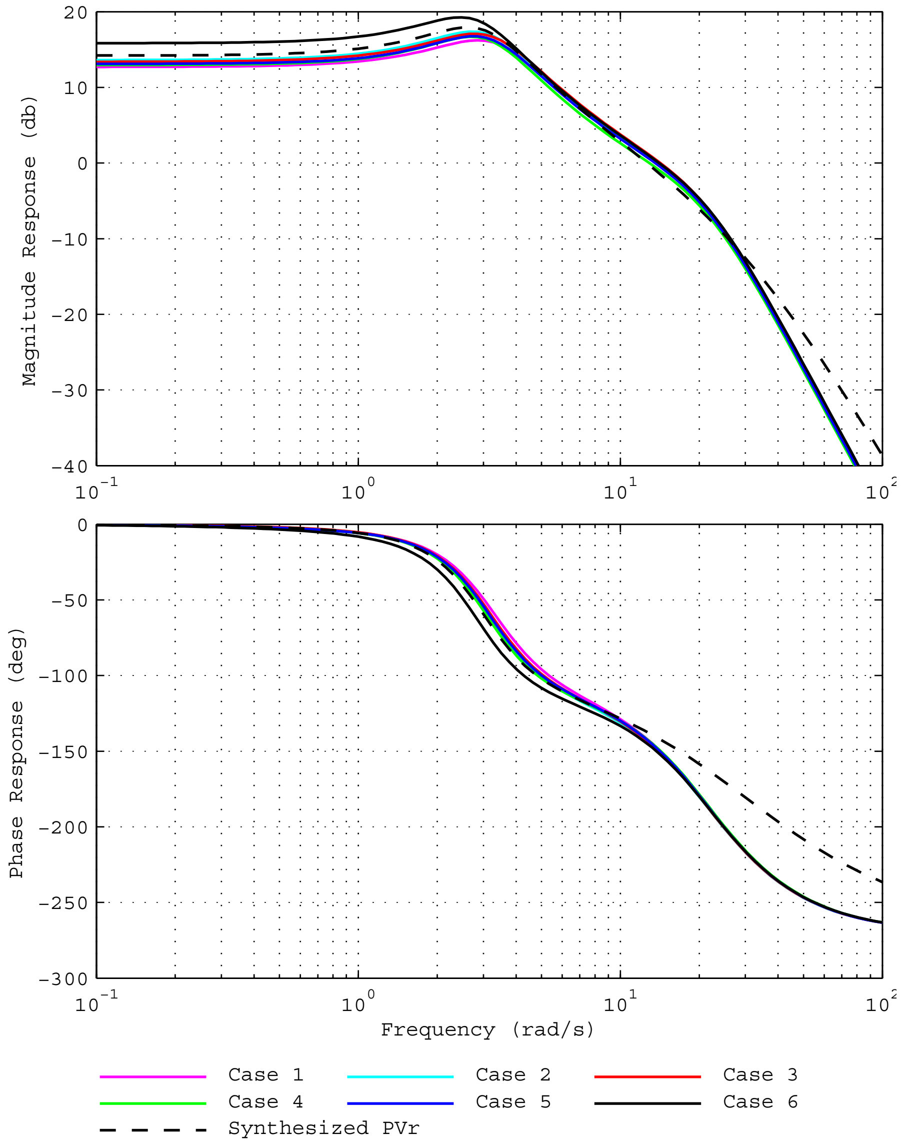


Figure 14 P-Vr characteristics, calculated and synthesized ($PVR(s)$), for generator NPS_5.

$$PVR(s) = 5.13(1 + s0.300)/[(1 + s0.033)^2(1 + s0.300 + s^2 0.111)]$$

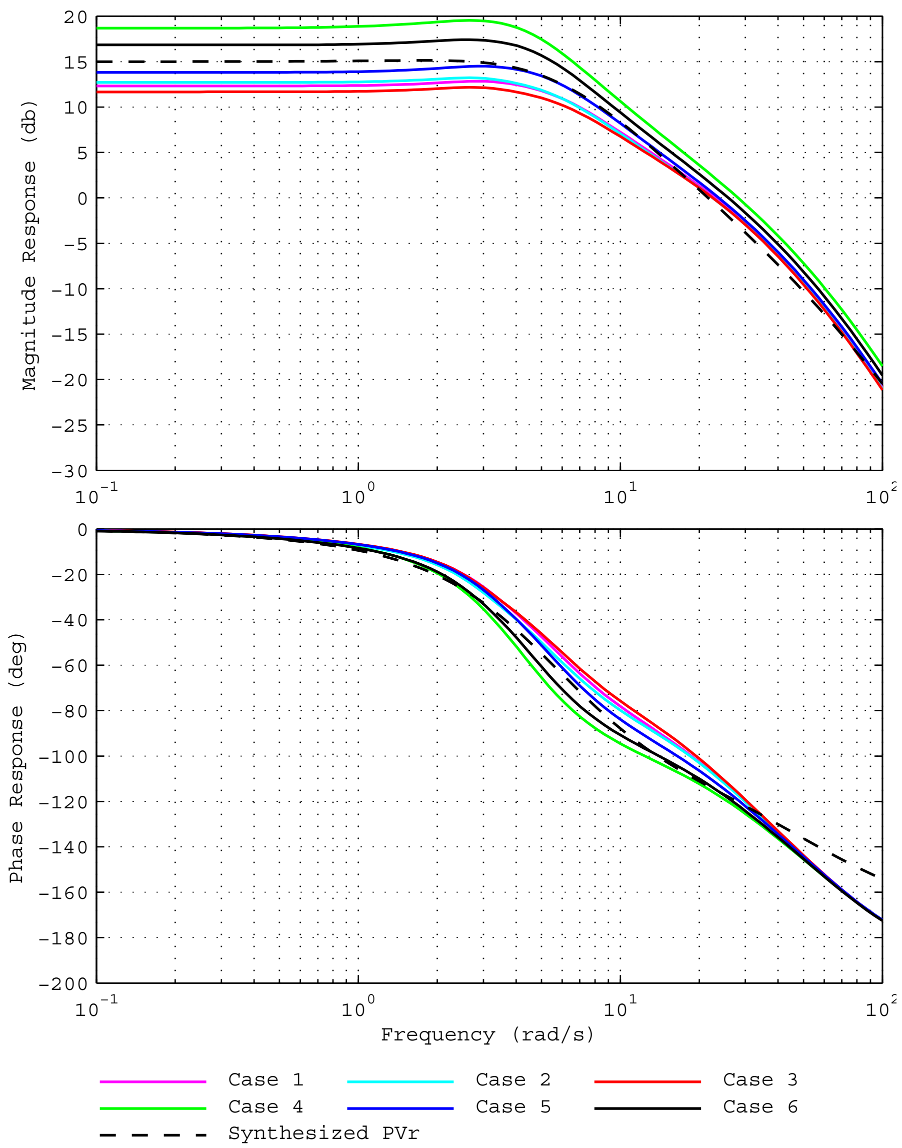


Figure 15 P-Vr characteristics, calculated and synthesized ($PVR(s)$), for generator PPS_5.

$$PVR(s) = \frac{5.62(1 + s0.350)(1 + s0.0667)}{(1 + s0.020)(1 + s0.167)(1 + s0.187)(1 + s0.200)}$$

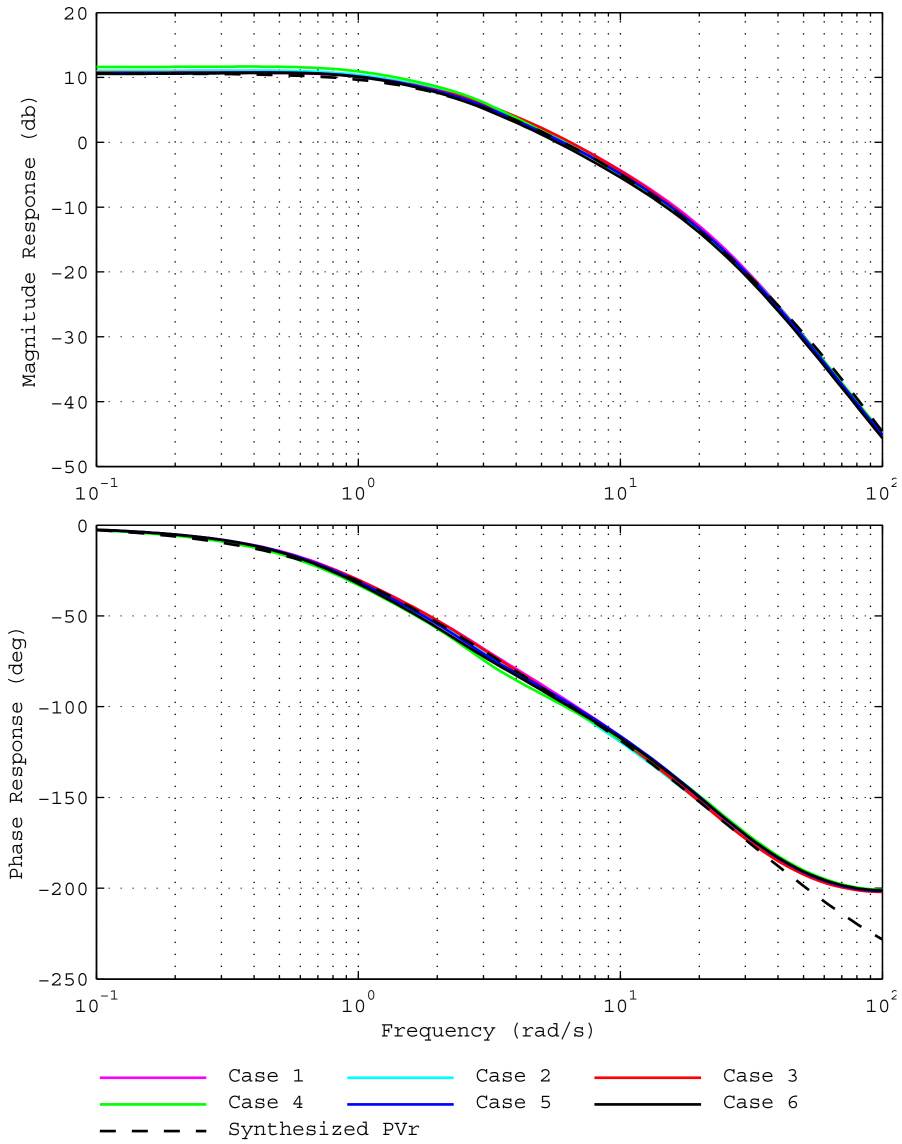


Figure 16 P-Vr characteristics, calculated and synthesized ($PVR(s)$), for generator TPS_5.
$$PVR(s) = 3.4/[(1+s0.500)(1+s0.0588)(1+s0.0167)]$$

8 Results of small-signal analysis for the six cases

Please note the Caveats listed in Section 2 before interpreting these results.

For each of the six cases the rotor modes of oscillation without and with all PSSs in service are listed in Table 2 to Table 7.

In Fig. 17 is shown the plot of the electro-mechanical modes for Case 1 as the PSS damping gains on all generators are increased from zero (no PSSs in service) to 30 pu in 5 pu steps. Note that the modes shift more or less directly into the left-half of the *s*-plane. Without the special compensation referred to in Section 7 for the inter-area modes, the frequencies of the inter-area modes tend to decrease relatively more than the local-area modes due to the effects of interactions [6], [11]; the damping of the inter-area modes is also poorer.

Table 2 Rotor modes. Case 1: PSSs out and in service. (Damping gains 20pu on rating)

Case1: No PSSs			Case 1: All PSS in service		
Real	Imag	Damping Ratio	Real	Imag	Damping Ratio
-0.175	10.442	0.017	-2.193	10.386	0.207
0.109	9.583	-0.011	-1.978	9.742	0.199
0.041	8.959	-0.005	-1.926	9.293	0.203
-0.557	8.634	0.064	-2.505	8.858	0.272
-0.260	8.368	0.031	-1.953	8.261	0.230
-0.612	8.047	0.076	-1.971	8.490	0.226
-0.439	7.965	0.055	-1.875	7.756	0.235
0.014	7.812	-0.002	-1.777	7.643	0.226
-0.189	7.724	0.024	-2.061	7.872	0.253
-0.617	7.425	0.083	-1.878	7.588	0.240
0.115	3.970	-0.029	-1.044	3.640	0.276
0.088	2.601	-0.034	-0.385	2.402	0.158
-0.016	2.028	0.008	-0.522	1.798	0.279

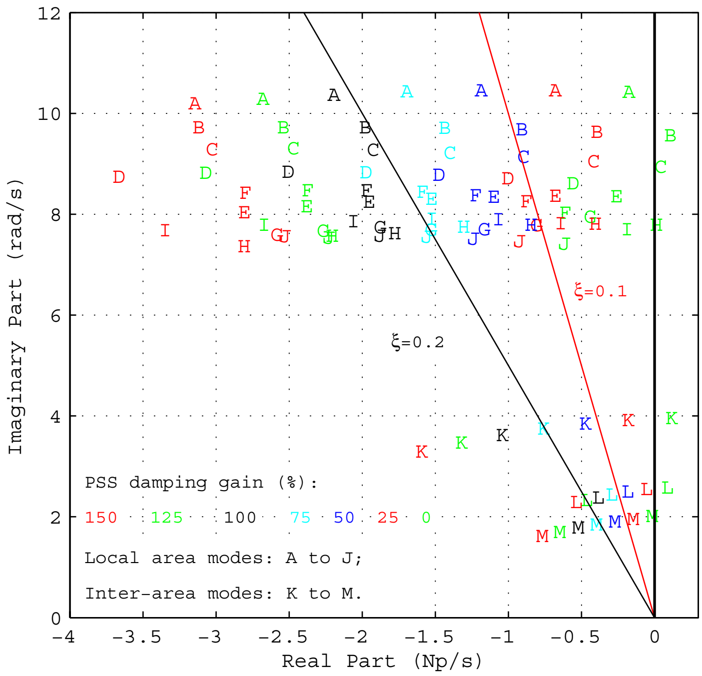


Figure 17 Rotor modes for Case 1 as the PSS damping gain on each generator is increased from zero (no PSSs in service) to 30 pu (150%) in 5 pu (25%) steps. (100% gain is equivalent to PSS damping gain De=20 pu on machine base)

Table 3 Rotor modes. Case 2: PSSs out and in service. (Damping gains 20pu on rating)

Case 2: No PSSs			Case 2: All PSS in service		
Real	Imag	Damping Ratio	Real	Imag	Damping Ratio
0.066	10.743	-0.006	-2.403	10.964	0.214
0.101	9.563	-0.011	-2.038	9.725	0.205
-0.250	9.261	0.027	-2.370	9.644	0.239
-0.922	8.613	0.106	-2.805	8.962	0.299
-0.534	8.669	0.062	-2.494	8.936	0.269
-0.184	8.482	0.022	-2.039	8.379	0.236
-0.700	8.293	0.084	-2.442	8.370	0.280
-0.208	7.929	0.026	-2.029	7.739	0.254
-0.065	7.385	0.009	-2.021	7.490	0.261
-0.485	7.570	0.064	-1.814	7.772	0.227
0.193	3.772	-0.051	-0.769	3.537	0.212
0.054	2.863	-0.019	-0.447	2.542	0.173
0.081	1.915	-0.042	-0.431	1.759	0.238

Table 4 Rotor modes. Case 3: PSSs out and in service. (Damping gains 20pu on rating)

Case 3: No PSSs			Case 3: All PSS in service		
Real	Imag	Damping Ratio	Real	Imag	Damping Ratio
-0.377	11.109	0.034	-1.909	11.244	0.167
0.101	9.555	-0.011	-2.037	9.724	0.205
-0.301	9.021	0.033	-2.278	9.100	0.243
-0.583	8.702	0.067	-2.519	8.914	0.272
-0.182	8.660	0.021	-2.025	8.376	0.235
-0.140	8.249	0.017	-1.948	8.492	0.224
-0.191	8.110	0.024	-2.011	7.727	0.252
-0.076	7.625	0.010	-1.932	7.535	0.248
-0.576	7.381	0.075	-1.933	7.800	0.241
-0.131	6.314	0.021	-2.030	5.909	0.325
0.011	4.090	-0.003	-1.119	3.707	0.289
0.020	2.727	-0.007	-0.428	2.418	0.174
-0.032	2.105	0.015	-0.580	1.860	0.298

Table 5 Rotor modes. Case 4: PSSs out and in service. (Damping gains 20pu on rating)

Case 4: No PSSs			Case 4: All PSS in service .†		
Real	Imag	Damping Ratio	Real	Imag	Damping Ratio
0.197	10.484	-0.019	-2.374	10.774	0.215
0.030	9.665	-0.003	-2.163	9.951	0.212
-0.173	9.369	0.018	-2.269	9.813	0.225
-1.541	8.276	0.183	-1.695	8.169	0.203
-0.178	8.779	0.020	-2.272	8.793	0.250
-0.561	8.581	0.065	-2.496	9.064	0.266
-0.211	8.278	0.025	-2.554	8.445	0.289
-0.508	8.522	0.060	-2.492	8.826	0.272
-0.431	8.211	0.052	-2.280	8.279	0.265
-0.190	7.200	0.026	-1.319	7.494	0.173
0.165	4.743	-0.035	-1.080	4.581	0.229
0.023	3.573	-0.007	-0.563	3.322	0.167
-0.009	2.678	0.003	-0.589	2.513	0.228
..† PSS of HPS_1 is OFF as it operates as a synchronous compensator in this case					

Table 6 Rotor modes. Case 5: PSSs out and in service. (Damping gains 20pu on rating)

Case 5: No PSSs			Case 5: All PSS in service		
Real	Imag	Damping Ratio	Real	Imag	Damping Ratio
0.181	10.940	-0.017	-2.409	11.257	0.209
0.086	9.570	-0.009	-1.988	9.762	0.200
-0.163	9.171	0.018	-2.093	9.395	0.217
-0.182	8.696	0.021	-2.187	9.119	0.233
-0.496	8.554	0.058	-2.471	8.828	0.270
-0.263	8.452	0.031	-2.024	8.382	0.235
-0.524	7.975	0.066	-2.382	7.969	0.286
0.008	7.896	0.000	-1.853	7.809	0.231
-0.157	7.736	0.020	-2.116	7.865	0.260
-0.765	7.241	0.105	-1.858	7.449	0.242
0.191	4.152	-0.046	-0.884	3.902	0.221
0.006	3.122	-0.002	-0.457	2.889	0.156
0.059	2.154	-0.027	-0.497	1.957	0.246

Table 7 Rotor modes. Case 6: PSSs out and in service. (Damping gains 20pu on rating)

Case 6: No PSSs			Case 6: All PSS in service …†		
Real	Imag	Damping Ratio	Real	Imag	Damping Ratio
0.276	10.390	-0.027	-2.217	10.708	0.203
0.318	10.138	-0.031	-2.142	10.652	0.197
-0.129	9.423	0.014	-2.069	10.017	0.202
-0.233	8.920	0.026	-2.522	9.541	0.256
-0.455	8.738	0.052	-2.381	9.023	0.255
-0.136	8.578	0.016	-2.320	8.506	0.263
-0.213	8.285	0.026	-2.579	8.453	0.292
-1.507	8.237	0.180	-1.701	8.168	0.204
-0.301	8.128	0.037	-2.076	8.242	0.244
-0.359	7.250	0.049	-1.598	7.553	0.207
0.200	4.810	-0.041	-1.078	4.644	0.226
0.054	3.552	-0.015	-0.565	3.298	0.169
0.036	2.597	-0.014	-0.520	2.451	0.207

…† PSS of HPS_1 is OFF as it operates as a synchronous compensator in this case.

9 References

[1] Web site for system loadflow files and results, and Matlab files. The University of Adelaide website address is:
http://www.eleceng.adelaide.edu.au/groups/PCON/PowerSystems/IEEE/BenchmarkData/index.html

The data are located in a ZIP file at:
http://www.eleceng.adelaide.edu.au/groups/PCON/PowerSystems/IEEE/BenchmarkData/AUdata.zip

[2] Gibbard, M.J. "Coordinated design of multi-machine power system stabilisers based on damping torque concepts". Proceedings IEE, Pt.C, Vol.135, July 1988, pp.276-284.

[3] Gibbard, M.J. "Robust design of fixed-parameter power system stabilisers over a wide range of operating conditions". IEEE Transactions on Power Systems, Vol. 6, No. 2, May 1991, pp 794-800.

[4] Pourbeik, P. and Gibbard, M.J., "Damping and synchronising torques induced on generators by FACTS stabilizers in multi-machine power systems", IEEE Transactions on Power Systems, Vol. 11, no. 4, Nov. 1996, pp. 1920-1925.

[5] Pourbeik, P. and Gibbard, M.J., "Simultaneous coordination of Power-System Stabilizers and FACTS device stabilizers in a multi-machine power system for enhancing dynamic performance", IEEE Transactions on Power Systems, Vol. 13, no. 2, May 1998, pp. 473-479.

[6] Gibbard, M.J., Vowles, D.J. and Pourbeik, P., "Interactions between, and effectiveness of, power system stabilizers and FACTS stabilizers in multi-machine systems", IEEE Transactions on Power Systems, Vol. 15, no. 2, May 2000, pp. 748-755. (In February 2001 this paper received the Prize Paper Award for 2000 from the Power System Dynamic Performance Committee of the IEEE PES.)

[7] CIGRE Technical Brochure no. 166 prepared by Task Force 38.02.16, “Impact of Interactions among Power System Controls", published by CIGRE in August 2000.

[8] Gibbard, M.J. and Vowles, D.J., "Discussion of 'The application of Power System Stabilizers to multi-generator plant' ", IEEE Transactions on Power Systems. Vol. 15, no. 4, Nov. 2000, pp. 1462-1464.

[9] Gibbard, M.J., Martins, N., Sanchez-Gasca, J.J., Uchida, N., Vittal, V. and Wang, L., "Recent Applications in Linear Analysis Techniques", IEEE Transactions on Power Systems. Vol. 16, no. 1, Feb. 2001, pp. 154-162.

[10] Pourbeik, P., Gibbard, M.J. and Vowles, D.J., "Proof of the equivalence of residues and induced torque coefficients for use in the calculation of eigenvalue shifts", IEEE Power Engineering Review, Power Engineering Letters, Vol. 22, no.1, Jan. 2002, pp. 58-60.

[11] Gibbard, M.J. and Vowles, D.J., "Reconciliation of methods of compensation for PSSs in multimachine systems", IEEE Transactions on Power Systems. Vol. 19, no. 1, Feb. 2004, pp. 463-472.

[12] E.V. Larsen and D.A. Swann, "Applying power system stabilizers: Part I - III", IEEE Transactions PAS, Vol. 100, pp. 3017-3046, 1981.

[13] P. Kundur, *Power System Stability and Control*, McGraw-Hill, Inc., 1994.

[14] Vowles, D.J. and Gibbard, M.J., “Mudpack - a software package for the analysis of the small-signal dynamic performance and control of large electric power systems”, School of Electrical & Electronic Engineering, The University of Adelaide, South Australia.

[15] IEEE Recommended Practice for Excitation System Models for Power System Stability Studies, IEEE Standard No:421.5-2005, ISBN:0-7381-4787-7.

Appendix I Data

Please note the Caveats listed in Section 2 before using this data.

I.1 Steady-state analysis

Table 1 (repeated) Six normal steady-state operating conditions

	Case 1 Load	Case 2 Load	Case 3 Load	Case 4 Load	Case 5 Load	Case 6 Load
Load Condition	Heavy	Medium-heavy	Peak	Light	Medium	Light
Total generation MW	23030	21590	25430	15050	19060	14840
Total load MW	22300	21000	24800	14810	18600	14630
Inter-area flows	(North to south)	(South to north)	(Hydro to N & S)	(Area 2 to N & S)	(N & S to pumping)	(~Zero transfers)
Area 4 to Area 2 MW	500	-500	-500	-200	300	0
Area 2 to Area 1 MW	1134	-1120	-1525	470	740	270
Area 1 to Area 3 MW	1000	-1000	1000	200	-200	0
Area 3 to Area 5 MW	500	-500	250	200	250	0

Table 8 Generation conditions for six loadflow cases

Power Station Rating Rated power factor	Case 1 No. units MW Mvar	Case 2 No. units MW Mvar	Case 3 No. units MW Mvar	Case 4: No. units MW Mvar	Case 5: No. units MW Mvar	Case 6: No. units MW Mvar
HPS_1 12 x 333.3 MVA 0.9 power factor lag	4 75.2 77.9	3 159.6 54.4	12 248.3 21.8	2 0 -97.4 Syn.Cond	3 -200.0 -26.0 Pumping	2 0 -102.2 Syn. Cond
BPS_2 6 x 666.7 MVA 0.9 power factor lag	6 600.0 95.6	5 560.0 38.9	6 550.0 109.1	4 540.0 -30.8	5 560.0 38.7	3 560.0 -53.5
EPS_2 5 x 555.6 MVA 0.9 power factor lag	5 500.0 132.7	4 480.0 60.5	5 470.0 127.6	3 460.0 -2.5	4 480.0 67.2	3 490.0 -7.3
MPS_2 6 x 666.7 MVA 0.9 power factor lag	6 491.7 122.4	4 396.0 17.8	6 536.0 96.5	4 399.3 -43.6	4 534.4 55.2	3 488.6 -61.2

Power Station Rating Rated power factor	Case 1 No. units MW Mvar	Case 2 No. units MW Mvar	Case 3 No. units MW Mvar	Case 4: No. units MW Mvar	Case 5: No. units MW Mvar	Case 6: No. units MW Mvar
VPS_2 4 x 555.6 MVA 0.9 power factor lag	4 375.0 132.8	3 450.0 82.4	2 225.0 157.0	3 470.0 9.4	2 460.0 83.1	3 490.0 3.7
LPS_3 8 x 666.7 MVA 0.9 power factor lag	7 600.0 142.3	8 585.0 141.1	8 580.0 157.6	6 555.0 16.6	8 550.0 88.1	6 550.0 9.4
YPS_3 4 x 444.4 MVA 0.9 power factor lag	3 313.3 51.5	4 383.0 63.3	4 318.0 49.6	2 380.0 -9.3	3 342.0 43.8	2 393.0 -6.9
CPS_4 3 x 333.3 MVA 0.9 power factor lag	3 279.0 59.3	3 290.0 31.4	3 290.0 32.0	2 290.0 -2.4	3 280.0 45.4	3 270.0 4.7
GPS_4 6 x 333.3 MVA 0.9 power factor lag	6 258.3 54.5	6 244.0 39.8	6 244.0 40.0	3 217.0 -3.5	5 272.0 50.4	3 245.0 3.9
SPS_4 4 x 444.4 MVA 0.9 power factor lag	4 350.0 52.3	4 350.0 47.2	4 350.0 47.3	3 320.0 14.2	4 340.0 46.3	2 380.0 25.2
TPS_4 4 x 444.4 MVA 0.9 power factor lag	4 350.0 128.7	4 350.0 116.5	4 350.0 123.2	3 320.0 -21.9	4 346.0 84.9	3 350.0 -32.6
NPS_5 2 x 333.3 MVA 0.9 power factor lag	2 300.0 25.3	2 300.0 -8.8	2 300.0 6.5	2 280.0 -52.5	2 280.0 -35.2	1 270.0 -42.2
PPS_5 6 x 166.7 MVA 0.9 power factor lag	4 109.0 25.2	5 138.0 36.9	6 125.0 32.6	1 150.0 2.2	2 87.0 3.5	2 120.0 -11.2
TPS_5 4 x 250 MVA 0.8 pf lag	4 200.0 40.1	4 200.0 53.0	4 180.0 48.8	3 180.0 -1.8	4 190.0 0.1	4 200.0 -9.7

Table 9 Voltages at synchronous machine and SVC terminals for loadflow Cases 1 to 6.

Bus No.	Case 1 Voltage Mvar	Case 2 Voltage Mvar	Case 3 Voltage Mvar	Case 4 Voltage Mvar	Case 5 Voltage Mvar	Case 6 Voltage Mvar
** Sync Machine	1.000 ##	1.000 ##	1.000 ##	1.000 ##	1.000 ##	.1.000 ##
205 SVC	1.055 -68.3	1.055 41.8	1.02 -5.2	1.045 -39.3	1.045 -118.3	1.045 -29.4
313 SVC	1.015 71.4	1.015 129.4	1.015 158.8	1.015 86.7	1.015 54.9	1.015 54.2
412 SVC	1.000 58.2	1.000 63.9	1.000 83.8	1.000 -52.2	1.000 22.8	1.000 -0.2
507 SVC	1.015 22.6	1.040 36.8	1.043 18.0	1.010 -4.0	1.015 13.8	1.000 -3.7
509 SVC	1.030 10.6	1.027 50.2	1.050 -63.4	1.030 -109.3	1.030 -123.8	1.030 -109.3

** Voltages at all synchronous machine terminals is 1.000 pu.
Reactive power outputs given in Table 8..

Table 10 Transmission Line Parameters: Values per circuit.

From bus / to bus	Line No.	Line r+jx; b (pu on 100MVA)
102 217	1,2	0.0084 0.0667 0.817
102 217	3,4	0.0078 0.0620 0.760
102 309	1,2	0.0045 0.0356 0.437
102 309	3	0.0109 0.0868 0.760
205 206	1,2	0.0096 0.0760 0.931
205 416	1,2	0.0037 0.0460 0.730
206 207	1,2	0.0045 0.0356 0.437
206 212	1,2	0.0066 0.0527 0.646
206 215	1,2	0.0066 0.0527 0.646
207 208	1,2	0.0018 0.0140 0.171
207 209	1	0.0008 0.0062 0.076
208 211	1,2,3	0.0031 0.0248 0.304
209 212	1	0.0045 0.0356 0.437
210 213	1,2	0.0010 0.0145 1.540
211 212	1,2	0.0014 0.0108 0.133
211 214	1	0.0019 0.0155 0.190
212 217	1	0.0070 0.0558 0.684
214 216	1	0.0010 0.0077 0.095
214 217	1	0.0049 0.0388 0.475
215 216	1,2	0.0051 0.0403 0.494
215 217	1,2	0.0072 0.0574 0.703
216 217	1	0.0051 0.0403 0.494

From bus / to bus	Line No.	Line r+jx; b (pu on 100MVA)
303 304	1	0.0010 0.0140 1.480
303 305	1,2	0.0011 0.0160 1.700
304 305	1	0.0003 0.0040 0.424
305 306	1	0.0002 0.0030 0.320
305 307	1,2	0.0003 0.0045 0.447
306 307	1	0.0001 0.0012 0.127
307 308	1,2	0.0023 0.0325 3.445
309 310	1,2	0.0090 0.0713 0.874
310 311	1,2	0.0000 -0.0337 0.000
312 313	1	0.0020 0.0150 0.900
313 314	1	0.0005 0.0050 0.520
315 509	1,2	0.0070 0.0500 0.190
405 406	1,2	0.0039 0.0475 0.381
405 408	1	0.0054 0.0500 0.189
405 409	1,2,3	0.0180 0.1220 0.790
406 407	1,2	0.0006 0.0076 0.062
407 408	1	0.0042 0.0513 0.412
408 410	1,2	0.0110 0.1280 1.010
409 411	1,2	0.0103 0.0709 0.460
410 411	1	0.0043 0.0532 0.427
410 412	1 to 4	0.0043 0.0532 0.427
410 413	1,2	0.0040 0.0494 0.400
411 412	1,2	0.0012 0.0152 0.122
414 415	1,2	0.0020 0.0250 0.390
415 416	1,2	0.0037 0.0460 0.730
504 507	1,2	0.0230 0.1500 0.560
504 508	1,2	0.0260 0.0190 0.870
505 507	1	0.0008 0.0085 0.060
505 508	1	0.0025 0.0280 0.170
506 507	1	0.0008 0.0085 0.060
506 508	1	0.0030 0.0280 0.140
507 508	1	0.0020 0.0190 0.090
507 509	1,2	0.0300 0.2200 0.900
Note: System frequency is 50 Hz.		

Table 11 Transformer Ratings and Reactance.

Buses		Number	Rating, each Unit (MVA)	Reactance per transformer	
From	To			% on Rating	per unit on 100MVA
101	102	g	333.3	12.0	0.0360
201	206	g	666.7	16.0	0.0240
202	209	g	555.6	16.0	0.0288
203	208	g	555.6	17.0	0.0306
204	215	g	666.7	16.0	0.0240
209	210	4	625.0	17.0	0.0272
213	214	4	625.0	17.0	0.0272
301	303	g	666.7	16.0	0.0240
302	312	g	444.4	15.0	0.0338
304	313	2	500.0	16.0	0.0320
305	311	2	500.0	12.0	0.0240
305	314	2	700.0	17.0	0.0243
308	315	2	370.0	10.0	0.0270
401	410	g	444.4	15.0	0.0338
402	408	g	333.3	17.0	0.0510
403	407	g	444.4	15.0	0.0338
404	405	g	333.3	17.0	0.0510
413	414	3	750.0	6.0	0.0080
501	504	g	333.3	17.0	0.0510
502	505	g	250.0	16.0	0.0640
503	506	g	166.7	16.7	0.1000

g - Generator/transformer unit; in service if associated generator is on-line.
Note: System frequency is 50 Hz.

Table 12 Switched Shunt Capacitor / Reactor banks (C/R) in service, Cases 1-6 (Mvar)

Bus Number	Case 1	Case 2	Case 3	Case 4	Case 5:	Case 6:
211	-	-	100 C	-	-	-
212	400 C	150 C	150 C	400 C	400 C	400 C
216	300 C	150 C	150 C	300 C	300 C	300 C
409	60 C	60 C	60 C	60 C	60 C	60 C
411	30 C	30 C	30 C	30 C	30 C	30 C
414	30 R	30 R	30 R	30 R	30 R	30 R
415	60 R	60 R	60 R	60 R	60 R	60 R
416	60 R	60 R	60 R	60 R	60 R	90 R
504	-	90 R	90 R	-	-	-

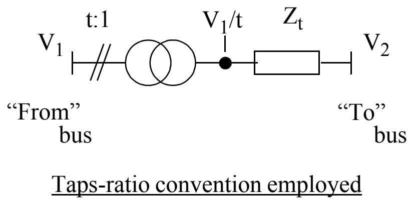


Figure 18 Transformer Taps Convention

The transformer tap ratios listed in Table 13 are based upon the convention shown in Fig. 18.

Table 13 Transformer Tap Ratios for Loadflow Cases 1 to 6

Buses		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
From	To						
101	102	0.939	0.948	0.948	1.000	1.000	1.000
201	206	0.943	0.948	0.939	1.000	0.971	1.010
202	209	0.939	0.948	0.939	1.000	0.971	1.010
203	208	0.939	0.948	0.939	1.000	0.971	1.010
204	215	0.939	0.948	0.939	1.000	0.971	1.010
209	210	0.976	0.990	0.976	0.976	0.976	0.976
213	214	1.000	1.000	1.000	1.000	1.000	1.000
301	303	0.939	0.935	0.930	1.000	0.961	1.000
302	312	0.952	0.952	0.952	1.000	0.961	1.000
304	313	0.961	0.961	0.948	0.961	0.961	0.961
305	311	1.000	1.000	1.000	1.000	1.000	1.000
305	314	1.000	1.000	1.000	1.000	1.000	1.000
308	315	1.000	0.960	1.000	1.000	1.000	1.000
401	410	0.939	0.939	0.939	1.000	0.952	1.010
402	408	0.952	0.952	0.952	1.000	0.952	1.000
403	407	0.952	0.952	0.952	1.000	0.952	1.000
404	405	0.952	0.952	0.952	1.000	0.952	1.000
413	414	1.000	1.000	1.000	1.000	1.015	1.000
501	504	0.952	0.952	0.952	1.000	0.985	1.015
502	505	0.962	0.930	0.930	1.000	0.995	1.020
503	506	0.962	0.930	0.930	1.000	0.985	1.020

For simplicity, loads are assumed to behave as constant impedances in the small-signal analysis.

Table 14 Busbar Loads (P MW, Q Mvar) for Cases 1 to 6

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6	
Bus No.	P	Q	P	Q	P	Q	P	Q	P	Q	P	Q
102	450	45	380	38	475	50	270	30	340	35	270	30
205	390	39	330	33	410	40	235	25	290	30	235	25
206	130	13	110	11	140	15	80	10	100	10	80	10
207	1880	188	1600	160	1975	200	1130	120	1410	145	1110	120
208	210	21	180	18	220	25	125	15	160	20	125	15
211	1700	170	1445	145	1785	180	1060	110	1275	130	1035	110
212	1660	166	1410	140	1740	180	1000	110	1245	125	1000	110
215	480	48	410	40	505	50	290	30	360	40	290	30
216	1840	184	1565	155	1930	200	1105	120	1380	140	1105	120
217	1260	126	1070	110	1320	140	750	80	940	95	750	80
306	1230	123	1230	123	1450	150	900	90	1085	110	900	90
307	650	65	650	65	770	80	470	50	580	60	470	50
308	655	66	655	66	770	80	620	100	580	60	620	100
309	195	20	195	20	230	25	140	15	170	20	140	15
312	115	12	115	12	140	15	92	10	105	15	92	10
313	2405	240	2405	240	2840	290	1625	165	2130	220	1625	165
314	250	25	250	25	300	30	180	20	222	25	180	20
405	990	99	1215	120	1215	120	730	75	990	100	730	75
406	740	74	905	90	905	90	540	55	740	75	540	55
407	0	0	0	0	0	0	0	0	0	0	0	0
408	150	15	185	20	185	20	110	10	150	15	110	10
409	260	26	310	30	310	30	190	20	260	30	190	20
410	530	53	650	65	650	65	390	40	530	55	390	40
411	575	58	700	70	700	70	420	45	575	60	420	45
412	1255	126	1535	155	1535	155	922	100	1255	130	922	100
504	300	60	200	40	300	60	180	20	225	25	170	20
507	1000	200	710	140	1100	220	640	65	750	75	565	65
508	800	160	520	105	800	160	490	50	600	60	450	50
509	200	40	70	15	100	20	122	15	150	15	117	15

Load Characteristics: Constant Impedance

I.2 Dynamic performance analysis

The parameters of the fourteen generators are listed in Table 15.

Table 15 Generator Parameters

Generator	Bus	Order	Rating MVA	No. of Units	H MWs/MVA	Xa pu	Xd pu	Xq pu	Xd' pu	Tdo' s	Xd" pu	Tdo" s	Xq' pu	Tqo' s	Xq" pu	Tqo" s
HPS_1	101	5	333.3	12	3.60	0.14	1.10	0.65	0.25	8.50	0.25	0.050	-	-	0.25	0.200
BPS_2	201	6	666.7	6	3.20	0.20	1.80	1.75	0.30	8.50	0.21	0.040	0.70	0.30	0.21	0.080
EPS_2	202	6	555.6	5	2.80	0.17	2.20	2.10	0.30	4.50	0.20	0.040	0.50	1.50	0.21	0.060

Gener-tor	Bus	Or-der	Rating MVA	No. of Units	H MWs/ MVA	Xa pu	Xd pu	Xq pu	Xd' pu	Tdo' s	Xd" pu	Tdo" s	Xq' pu	Tqo' s	Xq" pu	Tqo" s
MPS_2	204	6	666.7	6	3.20	0.20	1.80	1.75	0.30	8.50	0.21	0.040	0.70	0.30	0.21	0.080
VPS_2	203	6	555.6	4	2.60	0.20	2.30	1.70	0.30	5.00	0.25	0.030	0.40	2.00	0.25	0.250
LPS_3	301	6	666.7	8	2.80	0.20	2.70	1.50	0.30	7.50	0.25	0.040	0.85	0.85	0.25	0.120
YPS_3	302	5	444.4	4	3.50	0.15	2.00	1.80	0.25	7.50	0.20	0.040	-	-	0.20	0.250
CPS_4	402	6	333.3	3	3.00	0.20	1.90	1.80	0.30	6.50	0.26	0.035	0.55	1.40	0.26	0.040
GPS_4	404	6	333.3	6	4.00	0.18	2.20	1.40	0.32	9.00	0.24	0.040	0.75	1.40	0.24	0.130
SPS_4	403	6	444.4	4	2.60	0.20	2.30	1.70	0.30	5.00	0.25	0.030	0.40	2.00	0.25	0.250
TPS_4	401	6	444.4	4	2.60	0.20	2.30	1.70	0.30	5.00	0.25	0.030	0.40	2.00	0.25	0.250
NPS_5	501	6	333.3	2	3.50	0.15	2.20	1.70	0.30	7.50	0.24	0.025	0.80	1.50	0.24	0.100
TPS_5	502	6	250.0	4	4.00	0.20	2.00	1.50	0.30	7.50	0.22	0.040	0.80	3.00	0.22	0.200
PPS_5	503	6	166.7	6	7.50	0.15	2.30	2.00	0.25	5.00	0.17	0.022	0.35	1.00	0.17	0.035
Generator reactances in per unit on machine rating as base. For all generators the stator winding resistance (Ra) and damping torque coefficient (D) are both assumed to be zero. System frequency is 50 Hz.																

Table 16 Bus numbers for SVCs

SVC	ASVC_2	RSVC_3	BSVC_4	PSVC_5	SSVC_5
Bus	205	313	412	507	509
One unit assumed at the nominated bus. Nominal Device Base: 100 MVA					

I.2.1 Excitation System Parameters

Three basic types of excitation systems are employed, ST5B, AC4A and AC1A [15]. The parameters of the AVR have been tuned to ensure that the open-circuit generator under closed-loop voltage control is stable and satisfies the performance specifications. The small-signal models for the AC4A/ST5B and AC1A excitation systems are shown in Figure 19 and Figure 20, respectively. The model of Figure 19 represents the AC4A excitation system when T_{C1} and T_{B1} are set to zero.

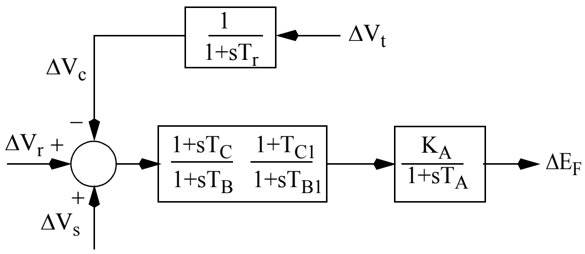


Figure 19 Small-signal model of excitation system types AC4A (when T_{B1}=T_{C1} =0) and ST5B.

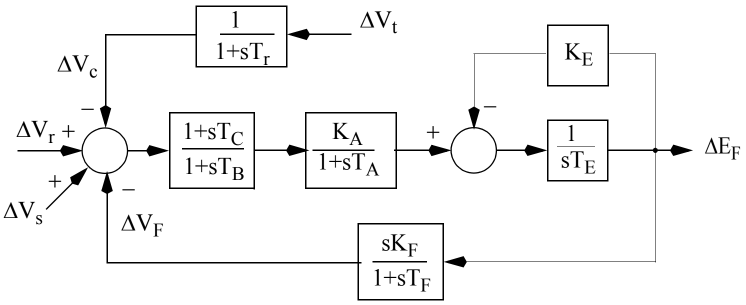


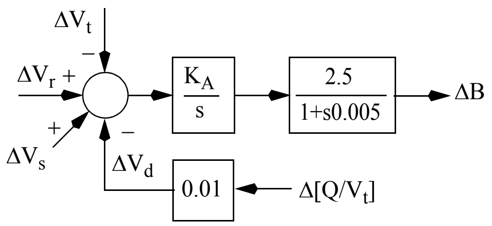
Figure 20 Small-signal model of a type AC1A Excitation System; demagnetizing effect of field current neglected

Table 17 Excitation System Parameters: 14-generator system

	HPS_1	BPS_2	EPS_2	MPS_2	VPS_2	LPS_3	YPS_3
Type	AC4A	AC4A	AC1A	AC4A	AC4A	AC4A	AC1A
T_r (s)	0	0	0	0	0	0	0
K_A (s)	200	400	400	400	300	400	200
T_A (s)	0.10	0.02	0.02	0.02	0.01	0.05	0.05
T_B (s)	13.25	1.12	0	1.12	0.70	6.42	0
T_C (s)	2.50	0.50	0	0.50	0.35	1.14	0
K_E	-	-	1.0	-	-	-	1.0
T_E (s)	-	-	1.0	-	-	-	1.333
K_F	-	-	0.029	-	-	-	0.020
T_F (s)	-	-	1.0	-	-	-	0.8

Table 18 ΔV Excitation System Parameters: 14-generator system (continued)

	CPS_4	GPS_4	SPS_4	TPS_4	NPS_5	TPS_5	PPS_5
Type	AC4A	AC4A	AC4A	AC4A	AC1A	ST5B	AC4A
T_r (s)	0.02	0	0	0	0	0	0
K_A	300	250	300	300	1000	400	300
T_A (s)	0.05	0.20	0.01	0.10	0.04	0.50	0.01
T_B (s)	9.80	0.0232	0.70	40.0	0	16.0	0.8
T_C (s)	1.52	0.1360	0.35	4.00	0	1.40	0.2
T_{B1} (s)	0	0	0	0	0	0.05	0
T_{C1} (s)	0	0	0	0	0	0.60	0
K_E	-	-	-	-	1.00	-	-
T_E (s)	-	-	-	-	0.87	-	-
K_F	-	-	-	-	0.004	-	-
T_F (s)	-	-	-	-	0.27	-	-



SVC	K_A
ASVC_2	500
RSVC_3	500
BSVC_4	500
PSVC_5	250
SSVC_5	250

Figure 21 Small-signal model of the SVCs' Excitation System (Nominal base 100 MVA)

I.3 Power System Stabiliser (PSS) Parameters

The structure of the PSS employing a speed-stabilising signal is shown in Figure 22. The design based on the P-Vr method of the block labelled 'Compensation TF and LP Filter' has been outlined in Section 6.3.

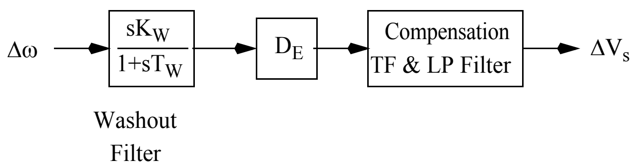


Figure 22 Structure of the PSS for analysis and design purposes

Assuming a single washout filter block is employed, the general form of the PSS TF is given in (2), i.e.

$$H_{PSS}(s) = kG_c(s) = k \cdot \left[\frac{sT_W}{1 + sT_W} \cdot \frac{1}{k_c} \cdot \frac{(1 + c_1 s + c_2 s^2)(1 + sT_a)\ldots}{(1 + sT_{b1})\ldots(1 + sT_1)(1 + sT_2)\ldots} \right].$$

The 'Compensation TF & LP Filter' (which excludes the Washout Filter) in Figure 22 represents a general form of that component in the above PSS TF given by:

$$H_c(s) = K_c \cdot \frac{(1 + c_1 s + c_2 s^2)(1 + sT_{a1})\ldots}{(1 + sT_{b1})\ldots(1 + sT_1)(1 + sT_2)\ldots} \quad \text{where} \quad K_c = 1/k_c \qquad (6)$$

In the PSS transfer function of Fig. 22, (i) the damping gain of the PSS is $k = D_e = 20$ pu on generator MVA rating, and (ii) the washout time constant T_W is 7.5 s.

I.3.1 PSS compensating transfer functions and parameters

Form of the fourth-order TF having real zeros:

$$H_c(s) = K_c \cdot \frac{1 + sT_a}{1 + sT_e} \cdot \frac{1 + sT_b}{1 + sT_f} \cdot \frac{1 + sT_c}{1 + sT_g} \cdot \frac{1 + sT_d}{1 + sT_h} \qquad (7)$$

Table 19 Compensation and LP Filter Parameters for PSS based on (7).

Generator	K_c	T_a	T_b	T_c	T_d	T_e	T_f	T_g	T_h
EPS_2	0.233	0.286	0.111	0.040	0	0.00667	0.00667	0.00667	0
PPS_5	0.178	0.200	0.187	0.167	0.020	0.350	0.0667	0.00667	0.00667
TPS_5	0.294	0.500	0.0588	0.0167	0	0.00667	0.00667	0.00667	0

Form of the fourth-order TF having real and complex zeros:

$$H_c(s) = K_c \cdot \frac{1 + sT_a}{1 + sT_d} \cdot \frac{1 + sT_b}{1 + sT_e} \cdot \frac{1 + as + bs^2}{(1 + sT_f)(1 + sT_g)} \qquad (8)$$

Table 20 Compensation and LP Filter Parameters for PSS based on (8)

Generator	K_c	T_a	T_b	a	b	T_d	T_e	T_f	T_g
MPS_2	0.333	0.010	0	0.10	0.0051	0.00667	0	0.00667	0.00667
YPS_3	0.298	0.050	0	0.5091	0.1322	0.00667	0	0.00667	0.00667

Generator	K_c	T_a	T_b	a	b	T_d	T_e	T_f	T_g
NPS_5	0.195	0.033	0.033	0.30	0.1111	0.300	0.00667	0.00667	0.00667

Form of the second-order TF having real zeros:

$$H_c(s) = K_c \cdot \frac{1+sT_a}{1+sT_e} \cdot \frac{1+sT_b}{1+sT_f} \tag{9}$$

Table 21 Compensation and LP Filter Parameters for PSS based on (9)

Generator	K_c	T_a	T_b	T_e	T_f
TPS_4	0.357	0.2083	0.2083	0.00667	0.00667
CPS_4	0.235	0.2777	0.1000	0.00667	0.00667
VPS_2	0.286	0.0708	0.0292	0.00667	0.00667

Form of the second-order TF having a pair of complex zeros:

$$H_c(s) = K_c \cdot \frac{1+as+bs^2}{(1+sT_e)(1+sT_f)} \tag{10}$$

Table 22 Compensation and LP Filter Parameters for PSS based on (10)

Generator	K_c	a	b	T_e	T_f
HPS_1*	0.769	0.3725	0.03845	0.00667	0.00667
BPS_2	0.278	0.1280	0.00640	0.00667	0.00667
LPS_3	0.625	0.1684	0.01180	0.00667	0.00667
GPS_4	0.303	0.1154	0.005917	0.00667	0.00667
SPS_4	0.316	0.0909	0.002067	0.00667	0.00667

* Note for HPS_1: PSSs are OFF in Cases 4 and 6. When motoring in Case5 the sign of the PSS output ΔV_S at the summing junction is negated.

I.4 Comparison of P-Vr and GEP methods

Table 23 P-Vr and GEP methods for the design of PSS compensation TFs

Comparison of two methods for the design of the PSS compensation transfer functions		
Feature	P-Vr	GEP [12]
1	Essentially an analytical frequency response approach using small-signal analysis software or Matlab. A wide range of normal and contingency operating conditions occurring on the power system is examined.	Originally a field-based frequency response method for tuning the PSS on a particular generator in a station for the particular operating condition(s) existing at the time.
2	Calculates magnitude and phase of the P-Vr over the complete range of rotor modes.	Field measurements provide the phase response $\Delta V_{term}/\Delta V_{ref}$ over a frequency range. Higher frequency measurements may be limited by resonances at lightly-damped local-area or intra-station modal frequencies.
3	The shaft dynamics are disabled.	The phase response of the TF $\Delta V_{term}/\Delta V_{ref}$ is close to that of the P-Vr TF because the speed perturbations associated with measurements are small (i.e. the shaft dynamics are virtually disabled).
4	PSS TF synthesized in *both* magnitude and phase from P-Vr characteristic.	PSS TF is synthesized from phase response.
5	Using magnitude information from P-Vr TF, damping gain k_i is set to provide the left-shift required to satisfy relevant system stability criteria.	The gain setting of the PSS (on site) is determined by increasing the gain until the onset of instability is detected; the gain is set to 1/3rd the latter value.

I.5 Machine Equations

In Table 15 both fifth- and sixth-order generator models are represented; in the fifth-order model the q-axis representation is simplified.

I.5.1 Sixth-order generator model

The following is a sixth-order model of a synchronous generator employed in PSS/E. In this model the "classically" defined, unsaturated operational-impedance parameters are used [13], section 4.1-2. A linearized form of these equations are provided in small-signal analysis packages such as [14].

Equations of motion:

$$\frac{d\delta}{dt} = \omega_0(\omega - 1), \tag{11}$$

$$2H\omega\frac{d\omega}{dt} = -D\omega(\omega - 1) + P_m - (v_D i_D + v_Q i_Q + r_a i_D^2 + r_a i_Q^2). \tag{12}$$

$$\omega_0 = 2\pi f_0,\ f_0 \text{ is 50 Hz},$$

where δ is the rotor angle (rad), and ω is the shaft speed in per-unit.

The rates of change of voltage behind transient reactance (E'_q and E'_d) and damper winding flux linkages (ψ_{kd} and ψ_{kq}) are given by:

$$\frac{dE'_q}{dt} = \frac{1}{T'_{d0}}(E_{fd} - X_{ad}i_{fd}); \tag{13}$$

$$\frac{d\psi_{kd}}{dt} = \frac{1}{T''_{d0}}(E'_q - \psi_{kd} - (X'_d - x_a)i_d); \tag{14}$$

$$\frac{dE'_d}{dt} = \frac{1}{T'_{q0}}X_{aq}i_{kq}; \tag{15}$$

$$\frac{d\psi_{kq}}{dt} = \frac{1}{T''_{q0}}(E'_d - \psi_{kq} - (X'_q - x_a)i_q). \tag{16}$$

The d- and q-axis components of the generator terminal voltage are:

$$v_d = -r_a i_d + X''_q i_q - \psi''_q, \tag{17}$$

$$v_q = -r_a i_q + X''_d i_d - \psi''_d. \tag{18}$$

The transformer voltages and the speed dependency of the rotational voltages in the stator equations are neglected.

The d- and q-axis components of the stator subtransient flux linkages, ψ''_d and ψ''_q, are:

$$\psi''_d = \left(\frac{X''_d - x_a}{X'_d - x_a}\right)E'_q + \left(\frac{X'_d - X''_d}{X'_d - x_a}\right)\psi_{kd}, \tag{19}$$

$$\psi''_q = \left(\frac{X''_q - x_l}{X'_q - x_a}\right)E'_d + \left(\frac{X'_q - X''_q}{X'_q - x_a}\right)\psi_{kq}. \tag{20}$$

The field current ($I_{fd} = X_{ad}i_{fd}$) is given by:

$$X_{ad}i_{fd} = K_{1d}E'_q + K_{2d}\psi_{kd} + K_{3d}i_d, \tag{21}$$

where

$$K_{1d} = 1 + \frac{(X_d - X'_d)(X'_d - X''_d)}{(X'_d - x_a)^2}, \quad \mathrm{K}_{2d} = 1 - K_{1d}, \quad \mathrm{K}_{3d} = \frac{(X_d - X'_d)(X''_d - x_a)}{(X'_d - x_a)}. \tag{22}$$

The q-axis excitation is:

$$X_{aq}i_{kq} = K_{1q}E'_d + K_{2q}\psi_{kq} + K_{3q}i_q, \tag{23}$$

where

$$K_{1q} = -\left[1 + \frac{(X_q - X'_q)(X'_q - X''_q)}{(X'_q - x_a)^2}\right], \qquad K_{2q} = -(1 + K_{1q}),$$

$$K_{3q} = \frac{(X_q - X'_q)(X''_q - x_l)}{(X'_q - x_a)}. \tag{24}$$

I.5.2 Fifth-order generator model

In the fifth-order model, only one damper winding is represented on the quadrature axis. The equations of motion and those for the direct-axis of the generator are therefore the same as for the sixth-order generator model. However, (15) and (16) for the quadrature axis are replaced by:

$$\frac{d\psi''_q}{dt} = \frac{1}{T''_{q0}}[\psi''_q - (X_q - X''_q)i_q]; \tag{25}$$

furthermore, the following equation replaces (20), (23) and (24):

$$\psi_q = \psi''_q - X''_q i_q. \tag{26}$$

I.6 Data and results files

PSS/E vs 29 loadflow data and results files are available on a website at the University of Adelaide [1]; the address is also given below. The loadflow file names take the form LF_Case0#_R3_S.raw and LF#_Report_R3_S.dat, respectively, where # is the case number, 1 to 6.

The following Matlab *.mat files, generated by a small-signal analysis package [14], are provided for Cases 1 & 6, (i) with no PSSs in service, and (ii) with PSSs in service:
(1) the ABCD matrices of the system are in files:
Case#_PSSs_Off_ABCD_Rev3_Matlab.mat and
Case#_PSSs_On_ABCD_Rev3_Matlab.mat;
(2) the eigenvalues, the eigenvectors and participation factors are in:
Case#_PSSs_Off_Eigs_Rev3_Matlab.mat and
Case#_PSSs_On_Eigs_Rev3_Matlab.mat,
where # is the case number, 1 or 6.

The website address is:
http://www.eleceng.adelaide.edu.au/groups/PCON/PowerSystems/IEEE/BenchmarkData/index.html

The data are located in a ZIP file at:
http://www.eleceng.adelaide.edu.au/groups/PCON/PowerSystems/IEEE/BenchmarkData/AUdata.zip

Information on the content of the data files is contained in a file ReadMe_Matlab_files.pdf in the AUdata.zip file.