Paper

A METHOD FOR CONSTRUCTING REDUCED MODELS EFFECTIVE FOR DESIGNING COORDINATED H_∞ PSS's

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This paper proposes an effective method for designing coordinated H_∞ PSS's to improve the damping of local and interarea oscillations. Target modes, types of inputs of the PSS, and effective locations for each controller are examined using the participation factor and residue concept. To realize coordination of the controllers, a method for constructing the reduced model effective for this design is presented, minimizing the uncertainty for each controller. With such a small uncertainty, a tight design which yields marginal robustness can be realized, increasing the performance of each controller as well as that of the total system. The influence of the reduced model on the controller characteristics is discussed. The effectiveness of the proposed control design is demonstrated through nonlinear numerical simulations in a five-machine seven-bus system under two critical operating conditions.

Key words: H_∞ -optimal control, PSS, Local/interarea Oscillation, Uncertainty, Reduced Model, Coordination

1. Introduction

A power system stabilizer (PSS) has been used to improve the damping of generators in a power system since 1940. The classical type of PSS based on a lead-lag compensator method has been widely used. Various techniques such as LQ type optimal control, adaptive control, neural network and a fuzzy controller have been proposed to design the PSS [1-3]. Although there have been a few successful cases, a weak point in such types of controllers is the lack of robustness. They could not fully cover the influence of plant uncertainties in designing the controller. To cope with this problem, the H_∞ optimal control theory developed by Zames[4] was adopted to design the PSS [6-8]. To improve the robustness and the performance of the standard H_∞ control, several techniques have been proposed to resolve the problem of the pole-zero cancellation and to select appropriate weighting functions, etc. [9-10]. However, these techniques are still being used for a one-machine system. Techniques for enhancement of interarea oscillation damping have been proposed in various papers such as in [11-12] that are useful in the design of a robust controller. However, the coordination of multiple controllers has not been extensively investigated . For a multimachine system consisting of many controllers, the investigation of the superiority of the H_∞ optimal control method to design and to coordinate all the controllers to obtain good performance and robustness for the whole system is still limited.

As is known, a reduced model with a smaller size of uncertainty representation is suited for the H_∞ controller design, which makes it possible to obtain a controller having small dimensions, leading to better performance and robustness. To realize coordination of multiple controllers, this paper proposes a method for constructing a reduced model effective for designing coordinated H_∞-PSS's by minimizing the uncertainty of each controller. With such a small uncertainty, a tight design which yields marginal robustness can be realized, increasing the performance of each controller as well as that of the total system.

The existence of uncertainty minimization process causes a significant difference between the proposed method and the previous methods [14-16]. The previous methods deal only with model error reduction at a fixed operating condition, while the proposed method with the uncertainty minimization for a set of operating conditions, which includes model error reduction. In addition, the proposed method adopts a more detailed and practical technique to take into account parameters as well as dynamic changes in the system. Target modes, types of inputs of the PSS, and effective locations for each controller are examined using the participation factor and residue concept.

The effectiveness of the proposed method is demonstrated through nonlinear numerical simulation under critical changes in operating conditions. To facilitate the design, a MATLAB software package is used [5].

2. Construction of Reduced Model for H∞-PSS's Coordination

In this paper, the purpose in designing coordinated H∞-PSS's is to independently design a local controller H^i so that all of the system controllers are coordinated. This means that :

- Each controller has a local feedback of local output variable y^i.
- Each controller will be designed independently
- Each controller will be responsible for only the target modes, but will cause no bad effects on another target modes.

To achieve this purpose, a method for constructing a reduced model for each controller is needed. The idea to construct the reduced model effective for designing coordinated H∞-PSS's will be explained in detail in this section.

Figure 1 describes a multimachine power system containing multiple H∞ PSS's to be designed where each PSS has a measurement $\boldsymbol{y^i}$ and an input $\boldsymbol{u^i}$. The following relation then holds when looking back into the system from each controller H^i of Figure 1:

$$y^i = G^{ii}(s)\,u^i + \sum_{i \neq j} G^{ij}(s)\,u^j \qquad \text{..........(1)}$$

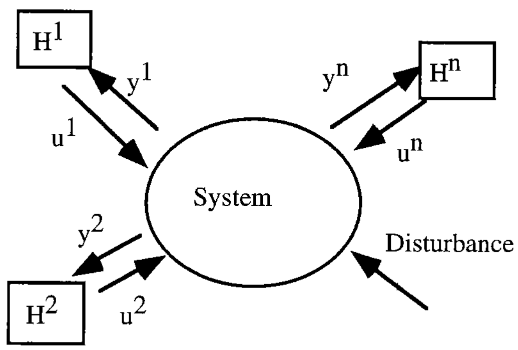

Fig. 1 Multimachine Power System Containing Multi H∞ PSS's

where G^{ij} is the transfer function of the open system from control signal u^j to feedback y^i, which is written in term of the matrix of system (A,B,C,D) as follows :

$$G^{ij}(s) = c^i(sI - A^{-1})b^j = \bar{c}^i diag(\frac{1}{s-\lambda_1}, \frac{1}{s-\lambda_2} ...)\bar{b}^j \text{..........(2)}$$

By defining

$$d^i = \sum_{i \neq j} G^{ij}(s)\,u^j \qquad \text{..........(3)}$$

Equation (1) can be rewritten as

$$y^i = G^{ii}(s)\,u^i + d^i \qquad \text{..........(4)}$$

The first term represents the input-output relation of the system while the second term is interpreted as interferences from other controllers. The second term should be stabilizing effects but may become disturbances by the other control actions of H^j, $j \neq i$. Such disturbance effects should be minimized when the coordination is performed. Figure 2 shows a diagram of equation (4).

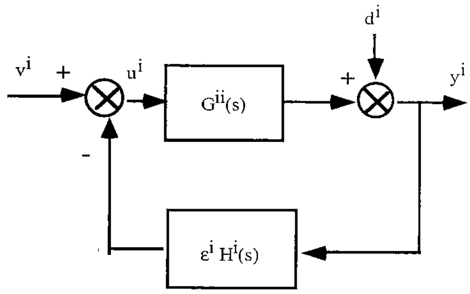

Fig. 2 General Feedback Configuration of Controller i

Equation (2) can also be written as another expression :

$$G^{ij} = \sum_k \frac{R_k^{ij}}{s-\lambda_k} = \frac{\bar{c}^{ik}\bar{b}^{kj}}{s-\lambda_k} \qquad \text{..........(5)}$$

The term λ_k in equation (5) is the eigenvalues of the open system $G^{ii}(s)$, while the term R_k^{ij} is called residue which express the effectiveness of a controller i to control mode k using feedback y^i. The eigenvalue sensitivity of mode k with respect to controller H^i is approximately given by :

$$\Delta\lambda_k = -R_k^{ii} H^i(\lambda_k)\,\varepsilon^i \qquad \text{..........(6)}$$

In the presence of multiple controllers, this implies :

$$\Delta\lambda_k = \sum_i -R_k^{ii} H^i(\lambda_k)\,\varepsilon^i \qquad \text{..........(7)}$$

This equation implies that mode k (λ_k) may effectively be controlled by controller H^i if $|R^{ii}|$ is large. It also implies that when λ_k and λ_l exist having opposite phases of R_k^{ii} and R_l^{ii} $(R_k^{ii} \cong -\alpha R_l^{ii})$ to each other, a reverse control effect will appear between λ_k and λ_l such as

$$\Delta\lambda_k = -R_k^{ii} H^i(\lambda_k) \cong \alpha R_l^{ii} H^i(\lambda_l) \cong -\alpha\Delta\lambda_l \qquad \text{..........(8)}$$

This observation suggests the design policy of distributed controllers :

(p1) Each controller is responsible for several target modes only when having a large residue $|R_k^{ii}|$.

(p2) Reverse control effects for non targets modes should be small. They will be target modes for other controllers so that all the modes are effectively controlled by the distributed set of controllers.

Based on the design policy above, $\mathbf{G^{ii}(s)}$ in equation (1) is divided into two terms as :

$$G^{ii}(s) = G_r^{ii}(s) + G_n^{ii}(s) = G_r^{ii}(s)(I + G_r^{ii}(s)^{-1} G_n^{ii}(s)) \qquad \text{.....(9)}$$

where

$$G_r^{ii}(s) = \sum_{k \in S_l(i)} \frac{R_k^{ii}}{s-\lambda_k}, \quad G_n^{ii}(s) = \sum_{l \in \bar{S}_l(i)} \frac{R_l^{ii}}{s-\lambda_l}$$

where $S_r(i)$ is a set of indices of target modes to be controlled by controller i while $\bar{S}_r(i)$ is that of non target modes. In the controller design, $G_r^{ii}(s)$ will be used as the reduced system for controller i, while $G_r^{ii}(s)^{-1}G_n^{ii}(s)$ will be included in the uncertainty as follows:

$$G^{ii}(s) = G_r^{ii}(s)(I + W_M^i(s)\Delta^i(s)) \qquad ....(10)$$

In the construction of the reduced system, the following steps are used to minimize the uncertainty of each controller i.

1. Choose target modes having large residues $|R_k^{ii}|$ and define a set of indices for the target modes of controller, $S_r(i)$. The local electro-mechanical oscillation mode of generator i must be included in this set. The interarea oscillation mode is also included only when $|R_k^{ii}|$ is relatively large compared with other locations so that the inter-area oscillation mode is controlled by one or more controllers.
2. If required, select mode $j \in \bar{S}_r(i)$ to be moved into $S_r(i)$ so that $|W_M(j\omega)\Delta^i(j\omega)|$ becomes small especially for the frequency range near the target modes $S_r(i)$.
3. Try to change the operating condition to determine if a non target mode $j \in \bar{S}_r(i)$ exists which is sensitive to the perturbation. Namely, for each reduced system $G_r^{ii}(s)$ of (10) defined by $S_r(i)$, determine whether $|W_M(j\omega)\Delta^i(j\omega)|$ is small. If not, then move the corresponding mode into $S_r(i)$.
4. Select the nominal operating condition for controller i so that the dampings of the target modes $S_r(i)$ are the worst of all the examined conditions. This selection of nominal condition makes possible the design of each controller in its critical condition.

All steps above must be repeated until all uncertainties are small enough. In step (1), PSSs which control the inter-area mode(s) are determined based on residues. More PSS will be selected for achieving more damping of the inter-area modes. That is, the number of PSS for inter-area mode(s) depends on the original plant condition and design requirements. Note that the aim of steps (2) and (3) is to minimize the uncertainty so that a tight design which yields marginal robustness can be realized and better performance can be gained. According to this aim, priority should be given to modes near the target modes that have low damping and high residues. This is reasonable because low damping modes cause high peaks in uncertainty. From procedure (1) – (4), we obtain $S_r(i)$ and its nominal operating condition for the controller to be designed i=1,2,.... The obtained $S_r(i)$ implies the modes that cannot be neglected in designing controller i.

3. Power System

The single line diagram of the studied system is shown in Figure 3. It consists of two subsystems connected by a long tie line. Area 1 consists of three generators (1,2 and 3), while area 2 consists of two generators (4 & 5). In the design stage, the generators are expressed by seven order models and are linearized around a nominal operating condition. It is noted that the single nominal condition is sufficient for multiple controller designs in this examination. The loads are represented as constant impedance and the AVR type is fast exciter without TGR[13]. The data for the overall system are given in the appendix.

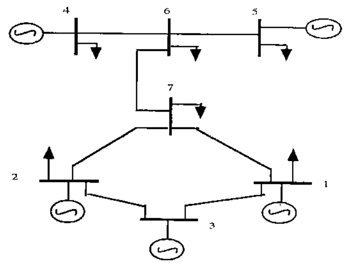

Fig.3 Power System Network

4. Design Steps

4.1 Examination of Input to PSS

It is known that a suitable input signal to the PSS depends on the network configuration as well as the locations of the generators. In this section, we present guidelines for the input selection.

We have examined various possible changing in operating conditions and identifies two representative conditions as follows:

- Peak Load I : Most severe peak load condition.
- Peak Load II: Peak load condition where the power direction in the tie line is reversed.

See appendix for the data for these conditions. It is noted that although we have examined the other various conditions to obtain the reduce model, they will be omitted in the following explanation for simplicity.

First, the eigenvalues of the system are computed using the data in the appendix for Peak Load I. In this system, 40 eigenvalues exist which are numbered in Table 1. Using the participation factor (PF) in Equation (11), analysis is then performed to determine the dominant state variables of each mode.

$$P_{ki} = \frac{\partial \lambda_i}{\partial a_{kk}} = \Phi_{ki} \cdot \Psi_{ik} \qquad ....(11)$$

where

P_{ki} : participation factor of state variable k on mode i;

Φ_{ki}, Ψ_{ki} : respectively elements of the right and left eigen vectors of system matrix A defined by

$A\Phi = \Lambda\Phi$, $\Psi = \Phi^{-1}$;

λ_i : The element of the diagonal matrix Λ that consists of all eigenvalues of the system;

a_{kk} : The element of system matrix A.

Table 1 System Modes

Modes		Freq	Damping	Dominant	Code
No	Eigenvalues	(Hz)	Ratio	State	
1,2	-1007 ± 595i	94.8	8.6E-01	Id,Iq of gen 1,2,3,4,5	IIA1
3.4	-187 ± 771i	122.8	2.4E-01	Ibid	IIA2
5,6	-4.1 ± 406i	64.7	1.0E-02	Id,Iq of gen 1,2,3	IL1
7,8	-14.6 ± 465i	74	3.1E-02	Ibid	IL2
9,10	-16.0 ± 473i	75.2	3.4E-02	Id,Iq of gen 4,5	IL3
11	-45.8			Efd of gen 1,2,3	EL1
12	-39.2			Ibid	EL2
13	-36.4			Ibid	EL3
14,15	-1.0 ± 22i	3.45	4.7E-02	Efd of gen 1,2,3,4,5	EIA
16	-31.1			Id,Iq of gen 1,2,3	IL4
17	-30.0			Efd of gen 4,5	EL4
18,19	-8.1 ± 20i	3.17	3.8E-01	Ibid	EL5
20	-25.1			Ibid	EL6
21	-23.3			Id,Iq of gen 1,2,3	IL5
22	-16.0			Iq of gen 1,2	IL6
23.24	-8.9 ± 9i	1.45	6.9E-01	Efd of gen 4,5	EL7
25,26	-7.0 ± 9i	1.45	6.0E-01	Efd of gen 1,2,3	EL8
27,28	-0.2 ± 11i	1.69	1.7E-02	Δω,Δδ of gen 4,5	ML1
29,30	-0.1 ± 9i	1.4	1.1E-02	Efd of gen 1,2,3	EL9
31,32	-0.1 ± 9i	1.4	7.7E-03	Δω,Δδ of gen 1,2,3	ML2
33.34	-0.2 ± 8i	1.3	2.2E-02	Δω,Δδ of gen 1,2,3	ML3
35	-10.9			Iq of gen 4,5	IL7
36,37	-7.5 ± 0.2i	0.03	1.0E+00	Efd of gen 1,2,3	EL10
38	-70.0			Efd of gen 1,2,3	EL11
39,40	-0.1 ± 1.5i	0.24	3.6E-02	Δω,Δδ of gen 1,2,3,4,5	MIA

Remarks :
IL : dominant state Id,Iq ,Local ; IIA : dominant state Id,Iq ,Interarea
ML : dominant state Δω,Δδ,Local ; MIA : dominant state Δω,Δδ , Interarea
EL : dominant state Efd ,Local ; EIA : dominant state Efd,Interarea

Tables 2-4 list the participation factors of these eigenvalues to state variables (Id,Iq,Efd,ω,δ). Based on this analysis, we have classified the existing modes into six types (see remarks under Table 1). Four critically damped mechanical modes are obtained as follows,

-0.2 ± 10.6 i (ML1)

-0.1 ± 8.8 i (ML2)

-0.2 ± 8.2 i (ML3)

-0.1 ± 1.5 i (MIA)

Note that all generators participate in interarea oscillation mode (MIA) that has outstanding features of low frequency oscillation around 0.24 Hz with a low damping ratio of 0.0361. For ML1, only generators 4 and 5 have a large contribution so that it is identified as local oscillation at area 2 with a frequency oscillation around 1.7 Hz and a damping ratio of 0.017. ML2 and ML3 are identified as local oscillations at area 1 because only generators 1,2 and 3 have a large contribution. Their frequency oscillations and damping ratios are 1.4 Hz and 0.008 for ML2 and 1.3 Hz and 0.022 for ML3. With such small damping ratio, the oscillations will take a long time to converge.

To add the damping of these mechanical modes as well as the other modes, several PSS's must be installed at suitable locations with the type of input that can effectively increase the damping.

Table 2 Participation Factor of Id & Iq

Mode's	Gen1		Gen2		Gen3		Gen4		Gen5	
number	Id	Iq	Id	Iq	Id	Iq	Id	Iq	Id	Iq
1,2	0.20	0.17	0.20	0.18	0.21	0.17	0.14	0.12	0.15	0.12
3,4	0.14	0.13	0.12	0.11	0.17	0.14	0.41	0.32	0.38	0.29
5,6	0.72	0.55	0.08	0.07	1.25	0.98	0.00	0.00	0.00	0.00
7,8	0.57	0.47	1.16	0.97	0.10	0.08	0.00	0.00	0.00	0.00
9,10	0.00	0.00	0.00	0.00	0.00	0.00	0.76	0.55	0.91	0.66
16	0.02	0.32	0.01	0.14	0.06	1.62	0.00	0.00	0.00	0.00
21	0.03	1.13	0.05	1.05	0.03	0.01	0.00	0.00	0.00	0.00
22	0.00	0.37	0.00	0.59	0.02	0.05	0.01	0.03	0.01	0.02
35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	1.27

Table 3 Participation Factor of Efd

Mode	Gen1	Gen 2	Gen 3	Gen4	Gen5
11	0.22	0.21	0.19	0.00	0.00
12	0.24	0.42	0.03	0.00	0.00
13	0.22	0.03	0.47	0.00	0.00
14,15	0.10	0.08	0.09	0.04	0.03
17	0.00	0.00	0.00	0.58	0.34
18,19	0.02	0.02	0.02	0.31	0.16
20	0.00	0.00	0.00	0.12	0.49
23,24	0.00	0.00	0.00	0.09	0.15
25,26	0.06	0.15	0.01	0.00	0.00
29,30	0.01	0.01	0.01	0.00	0.00
36,37	2.25	0.24	3.03	0.00	0.00
38	0.21	0.02	0.29	0.00	0.00

Table 4 Participation Factor of ω,δ

Mode's	Gen1		Gen 2		Gen3		Gen4		Gen5	
number	ω	δ	ω	δ	ω	δ	ω	δ	ω	δ
27,28	0.02	0.02	0.01	0.01	0.00	0.00	0.17	0.17	0.32	0.32
31,32	1.00	1.13	0.35	0.36	0.30	0.31	0.03	0.03	0.02	0.02
33,34	0.65	0.75	0.33	0.34	0.34	0.34	0.06	0.06	0.02	0.03
39,40	0.11	0.33	0.10	0.18	0.11	0.19	0.12	0.19	0.11	0.17

Using the residue concept, two alternative inputs Δω and ΔP are analyzed for each generator location with the results shown in Table 5. From this table, it is known that Δω is better than ΔP as a controller input for all mechanical modes. For local oscillations, all generators in each area can be effectively used to damp the corresponding local mode. Generators 1 & 5 are suitable locations to damp interarea oscillation as can be seen from the residue values that are larger compared to other generators.

4.2 Designing Reduced Nominal Model

From the previous analysis, it has been concluded that generators 1 and 5 are suitable locations to damp local and interarea oscillations and Δω is a suitable input. According to this result, we will now construct reduced nominal models for designing controllers at generators 1 and 5. Note that the reduced models are constructed based on Peak Load I Operating Condition (see Appendix). As an example, we will give a detailed explanation to design the reduced nominal model for generator 1 only. The same procedure is applied for generator 5. Following the guideline given in section 2, the reduced system $G_r(s)$ for generator 1 is determined as follows,

Table 5 System Residues

Code of Modes	Input Type	Controller's Location				
		Gen1	Gen2	Gen3	Gen4	Gen5
IIA1	Pe	1E-04	1E-04	1E-04	1E-03	5E-03
	ω	1E-06	1E-06	1E-06	2E-05	4E-05
IIA2	Pe	0E+00	0E+00	0E+00	2E-03	4E-03
	ω	1E-06	1E-06	1E-06	6E-05	9E-05
IL1	Pe	5E-05	6E-06	8E-05	0E+00	1E-06
	ω	3E-06	4E-07	5E-06	0E+00	0E+00
IL2	Pe	9E-05	2E-04	1E-05	0E+00	1E-05
	ω	5E-06	1E-05	8E-07	8E-08	7E-07
IL3	Pe	0E+00	0E+00	0E+00	2E-03	3E-03
	ω	0E+00	0E+00	0E+00	9E-05	2E-04
EIA	Pe	7E-02	6E-02	5E-02	8E-03	4E-02
	ω	7E-02	6E-02	6E-02	8E-03	4E-02
EL5	Pe	1E-02	1E-02	1E-02	3E-02	2E-01
	ω	1E-02	2E-02	1E-02	3E-02	2E-01
EL7	Pe	2E-03	1E-02	1E-03	9E-02	3E-01
	ω	2E-03	2E-02	3E-03	1E-01	5E-01
EL8	Pe	2E-01	6E-01	6E-02	4E-03	1E-03
	ω	3E-01	1E+00	1E-01	6E-03	3E-03
ML1	Pe	1E-02	1E-02	4E-03	8E-02	2E-01
	ω	2E-02	2E-02	8E-03	2E-01	4E-01
EL9	Pe	4E-02	2E-01	3E-01	5E-04	1E-04
	ω	8E-02	6E-01	7E-01	1E-03	3E-04
ML2	Pe	7E-01	2E-01	1E-01	1E-02	8E-03
	ω	2E+00	5E-01	3E-01	3E-02	2E-02
ML3	Pe	4E-01	1E-01	8E-02	7E-03	1E-02
	ω	1E+00	3E-01	2E-01	2E-02	3E-02
EL10	Pe	7E+00	5E-01	6E+00	5E-02	6E-03
	ω	1E+01	2E+00	3E+01	1E-01	2E-02
MIA	Pe	1E-02	3E-03	2E-03	7E-04	8E-03
	ω	7E-02	2E-02	2E-02	6E-03	7E-02

From Table 5, we have chosen core target modes consisting of mechanical local and interarea oscillations having large residues relating to generator 1. That is, we set $S_r(1)$ = {ML2, ML3, MIA } which implies that the reduced system for the controller at generator 1 consists of the local modes $-0.1\pm 8.8i$, $-0.1\pm 8.2i$ and the interarea mode $-0.1\pm 1.5\,i$ and that the other modes are treated as uncertainty. Figure 4(a) shows the uncertainty $W^i_M(s)\Delta^i(s)$ in (10) for this reduced model.

Next, determine if suitable modes exist in $\bar{S}_r(1)$ to be included in $S_r(1)$. Modes EIA and EL9 are selected to be included in $S_r(1)$ because they have low dampings and large residues as can be seen from Table 5. It is noted that modes having large residues but good dampings are excluded because they do not affect the stability significantly. Also, modes having low dampings and low residues must be excluded as uncertainty because they cannot be controlled effectively by controller 1; these modes will be treated as target modes of other controllers. At this stage we have $S_r(1)$ = {ML2, ML3, MIA, EIA, EL9}. Figure 4(b) shows the uncertainty $W^i_M(s)\Delta^i(s)$ in (10) after this step. From the figure, it is seen clearly that the uncertainty has successfully been reduced especially at the peaks near the target modes.

To evaluate the influence of operating condition changes on the uncertainty, another critical condition is examined (Peak Load II). Computing the uncertainty for this operating condition using the reduced model found before, it is proved that the reduced model is already sufficient.

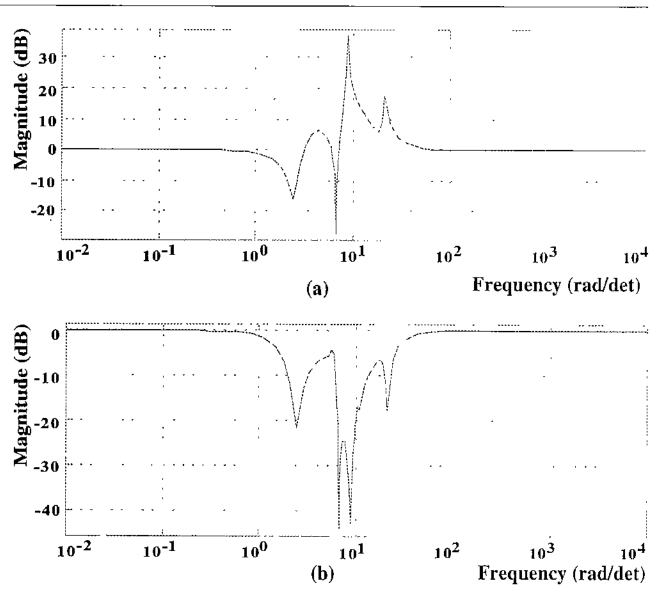

Fig.4 Uncertainty Under Peak Load I Operating Condition for Different Reduced Model $S_r(1)$
(a) $S_r(1)$ = { ML2, ML3, MIA }
(b) $S_r(1)$ = {ML2, ML3, MIA, EIA, EL9 }

Last, by comparing the damping of the target modes between two critical operating conditions, which result is not shown here, it is proved that Peak Load I is the worst operating condition. Thus, this operating condition will be selected as the nominal operating condition to permit the design of controller 1 to be in its critical condition.

From the above explanation, we obtain $S_r(1)$ = {ML2, ML3, MIA, EIA, EL9} as the final reduced model to design the controller at generator 1 and Peak Load I as the nominal operating condition. As a comparison, in the next, section, reduced model $S_r(1)$ = {ML2, ML3, MIA} will also be used to design the same controller.

4.3 Selecting Weighting Functions

Three weighting functions used in this paper are W_p, W_A and W_M respectively representing the desired disturbance attenuation, the maximum allowable additive and multiplicative uncertainty [5]. W_p should be designed to attenuate low frequency disturbance to increase the controller's performance. W_A is used to limit the signal output of the controller not to be too large for the excitation circuit. To guarantee that the controller under design will be robust against uncertainty, the magnitude of W_M should enclose the magnitude of multiplicative uncertainty expressed as $W_M(s)\Delta(s)$ in equation (10). In addition, W_M should also be chosen such that $\Delta(s)$ in equation (10) will be as flat as possible so that a tight design can be realized, increasing the performance of the controller. For that purpose, the weighting functions are found to be:

$W_M = (s^2+100.01s+10)/(s^2+11s+10)$ ....(12)

$W_P = 10(s+300)/(s+10)$ ....(13)

$W_A = (0.1s^2+100.001s+1)/(0.1s^2+1.1s+1)$ ....(14)

These weighting functions together with the reduced model found before will be used to compute the controller. Figure 5 shows weighting functions W_M and W_M' together with the uncertainties computed before. In the case of W_M, it can be predicted that the system will be robust if reduced model $S_r(1)$ = { ML2, ML3, MIA,EIA,EL9} is used (see Unc(1) in Fig. 5). In the case where $S_r(1)$ = { ML2, ML3, MIA} is used (see Unc(2) in Fig. 5), a larger weighting function is needed (for example, the one expressed as the dot line in Figure 5 (W_M')), but this will lead to worse performance.

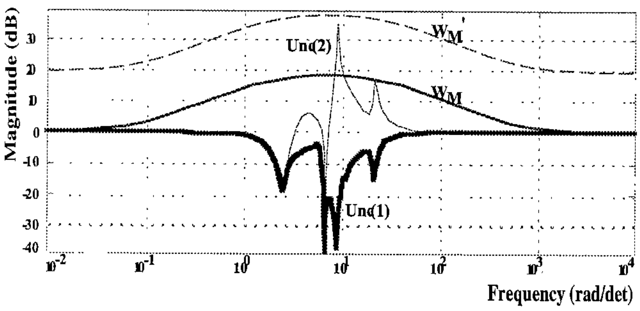

Fig.5 Weighting Function W_M and Uncertainties of Different Reduced Model

5. Simulation and Evaluation

To show the effectiveness of the proposed method regarding the system's robustness and performance, simulation is conducted by applying a step disturbance as large as 0.01 p.u at the voltage of generator 1 and then analyzing the output Δω of generator 1.

Figure 6 compares the response time of Δω of generator 1 between an open loop system (system without PSS) (a), a system with only one PSS at generator 1 (b) and a system with PSS's at generators 1 and 5 (c). The figure shows clearly not only performance enhancement by the controllers but also good coordination between the controllers. From this figure, it is known that the open loop system consists of a local mode which converges in about 20 sec and an interarea mode which converges in more than 50 sec (see Fig.a). By installing the PSS at generator 1, both of these modes converge in a shorter time, about 5 sec for the local mode and 35 sec for the interarea mode (see Fig.b). Adding the PSS at generator 5, as expected, will not affect the local mode of generator 1 as shown in Fig.c. However, the interarea mode is greatly influenced as can be seen from the convergence time which become only about 15 sec.

Figure 7 shows a comparison of Δω of generator 1 when the controller is designed using a different reduced model discussed in the last section. The performance described by *the bold line* resulted from the controller based on the reduced model $S_r(1)$ = {ML2, ML3, MIA,EIA,EL9} which corresponds to the weighting function W_M in Figure 5. The other one resulted from

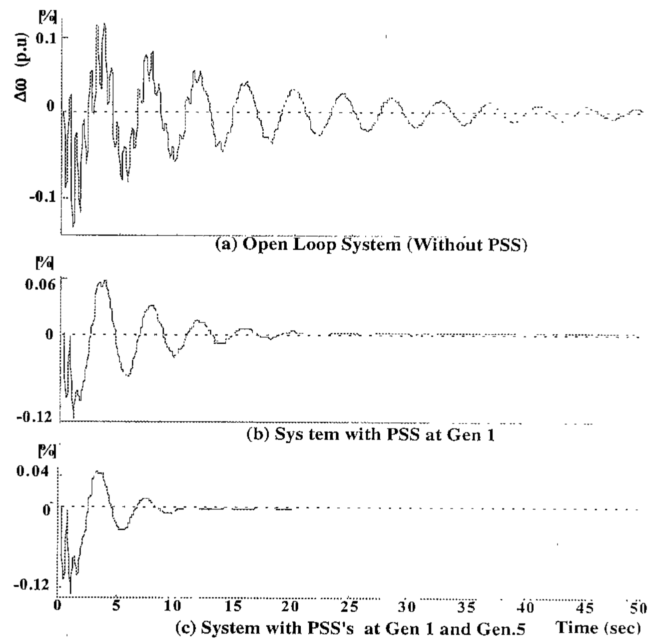

Fig.6 Step Response of Δω of Generator 1 Influenced by PSS's at Gen.1 and 5

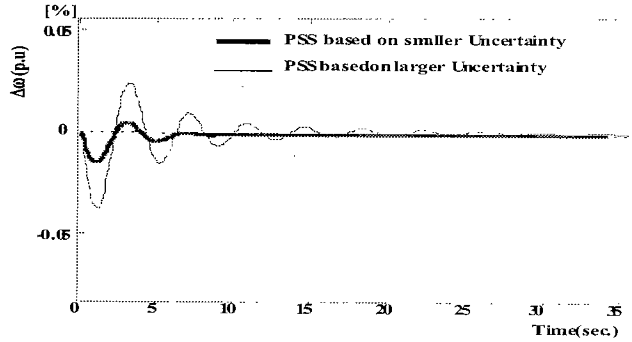

Fig.7 Step Response of Δω of Generator 1 Influenced by PSS at Gen.1 Based on Different Reduced Model

the controller based on reduced model $S_r(1)$ = { ML2, ML3, MIA} which corresponds to weighting function W_M' in Figure 5. From Figure 7, it is clear that if the controller is designed using a larger weighting function (larger uncertainty) the performance becomes worse compare to the others. Therefore, it can be concluded that, if we want to enhance the performance, the reduced model must be carefully selected so that the uncertainties

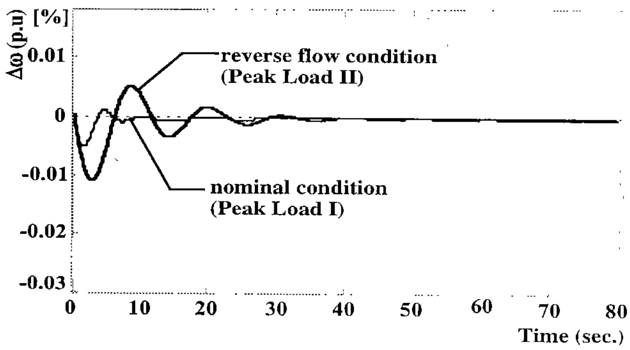

Fig.8 Step Response of Δω of Generator 1 for Two Critical Operating Conditions

are minimized. The robustness of the controller based on the reduced model $S_r(1)$ = { ML2, ML3, MIA,EIA,EL9} for two critical operating conditions (Peak Load I & II mentioned in section 4) is shown in Figure 8. From that figure, it is proved that the designing method developed here can provide sufficient robustness for the two operating conditions being considered.

It is noted that although only a single mechanical inter-area mode exists in this simulation, the proposed method will work properly when there exist multiple critical inter-area modes where such critical modes will be identified as target modes which will then be stabilized by the distributed controllers in cooperated manner.

6. Conclusion

The robustness and performance of the coordinated H_∞ PSS's are influenced by the reduced model used to design each controller. An important issue in constructing a suitable reduced model is to minimize system uncertainties in the model reduction. To realize the coordination of controllers, a method for constructing the reduced model effective for this objective is presented. As demonstrated in the nonlinear simulation, the performance of each controller as well as of the total system is increased when each controller is designed through the proposed method. At present, no major difficulties are expected in the application to a large power system.

(Manuscript received December 15,1999, revised July 24,2000)

Appendix

MVA base : 1000 MVA, frequency = 60 Hz.

Gen.1 : MVA base:1900 xd=0.85 xq=0.7 xd'=0.3 xq'=0.55 xd''=0.2 xq''=0.2 tdo'=5 tdo''=0.053 tqo''=0.123 H=4.5

Gen.2 : MVA base:1400 xd=0.85 xq=0.7 xd'=0.3 xq'=0.55 xd''=0.2 xq''=0.2 tdo'=5 tdo''=0.053 tqo''=0.123 H=4.5

Gen.3 : MVA base:1944 xd=0.88 xq=0.69 xd'=0.3 xq'=0.55 xd''=0.2 xq''=0.2 tdo'=5 tdo''=0.06 tqo''=0.09 H=4.5

Gen.4 : MVA base:6633 xd=0.9 xq=0.68 xd'=0.3 xq'=0.55 xd''=0.24 xq''=0.27 tdo'=7.6 tdo''=0.09 tqo''=0.19 H=5.07

Gen.5 : MVA base:6000 xd=1 xq=0.7 xd'=0.3 xq'=0.55 xd''=0.25 xq''=0.2 tdo'=8 tdo''=0.09 tqo''=0.2 H=5

AVR Data: Fast Exciter, T_R=0.01 K_A=25 T_A=0.03 T_C=T_B=0 (NO TGR)

Network Data (R + jX (p.u)):

1 – 3 : 0.003 + j 0.038; 2 – 3 : 0.005 + j 0.076;
4 – 6 : 0.0029 + j 0.0734; 7 – 1 : 0.019 + j 0.245;
7 – 2 : 0.015 + j 0.225; 6 – 7 : 0.0 + j 0.039; 6 – 5 : 0.004+ j 0.057.

Peak Load I (nominal condition) in p.u :

Bus 1 (P/Q) : 2.405 /0.467; Bus 2 (P/Q) : 0.692 /0.184;
Bus 3 (P/Q) : 0.688 /0.235; Bus 4 (P/Q) : 0.062 /0.024;
Bus 5 (P/Q) : 2.884 /0.196; Bus 6 (P/Q) : 0.005 /0.079;
Bus 7 (P/Q) : 0.846 /0.009

Peak Load II (reverse flow condition) in p.u:

The same as Peak Load I, only loads at Bus 6 and 7 are interchanged.

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