Selection of Weight Functions for Unstructured Uncertainty in the Synchronous Generator Model

Konstantin Gerasimov[1]

Abstract – **An output multiplicative representation of uncertainties in the synchronous generator unit model is discussed for the purposes of the stability analysis of the electromechanical modes under small disturbances. A study is carried out analyzing the influence of the choice of nominal model and calculation algorithms over the weight functions.**

Keywords – **weight functions, unstructured uncertainty, synchronous generator.**

I. Introduction

The electric power system (EPS) analysis under small disturbances is based on a mathematical description linearized around a certain operating point. In fact the operating point depends on a number of factors and is dynamic in time. This is why the linearized model should be treated as uncertain model. Another source of uncertainties is the inaccurate information about the schematic parameters of the elements of EPS. When the source of uncertainties is known, a common practice is to use structured representation of the uncertainties [1-3]. This approach was used in [4] and was shown that it is not applicable for modeling EPS because of the very high order of the obtained model. This is why it is appropriate to represent the uncertainty of the system as unstructured. Main problem with this method is the determination of adequate weight functions that properly describe the uncertainty effect in the model. In most books this problem is not treated thoroughly for MIMO systems and even less for the case of EPS.

When the sources of uncertainty are known, usually the unstructured uncertainty weight functions are determined from the bounds of the frequency responses of the family of models built under the conditions of different combinations of values of the uncertain quantities amongst their range of variation. The ranges of the schematic parameters are relatively small in comparison with the variation of the regime parameters (caused by the change of the operating point) and this is why the latter have bigger influence. The purpose of this paper is to share the experience with calculation of appropriate unstructured uncertainty weight functions for representation of the operation point changes.

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II. Test Model

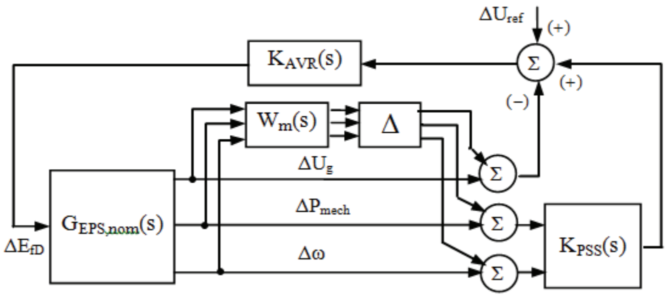

Fig. 1. Structural scheme of the model of single machine infinite bus system with multiplicative output uncertainty and AVR and PSS

In Fig. 1 is shown the structural scheme of the model of single machine infinite bus (SMIB) system ($G_{EPS,nom}(s)$). The generator is equipped with AVR ($K_{AVR}(s)$) and PSS ($K_{PSS}(s)$). The uncertainty is presented as output multiplicative unstructured, having matrix transfer weight function $W_m(s)$. The generator parameters are X_d=1.6 p.u., X_q=1.6 p.u.; X_σ=0.15 p.u., X_d'=0.266 p.u., X_d"=0.205 p.u., Xq"= 0.205 p.u., T_{d0}=5.8 s, T_{d0}"=0.13, T_{q0}"=0.13 s, T_J=6.3 s. The connecting power line has resistance X_{TW}=0.5 p.u. The AVR is type UNITROL F and the PSS is type PSS2A.

In the studied SMIB system, the independently changing regime parameters (i.e. changed by external for the system signals) are: the AVR reference ΔU_{ref}, voltage of the generalized system ΔU_s, and turbine power ΔP_{mech}. Their allowable ranges of change are approximately ΔU_{ref}=1÷1.05 p.u., ΔU_s=0.95÷1.05 p.u. and ΔP_{mech}= 0.2÷0.85 p.u. (for steam turbine, with $P_{base} = S_{G.nom}$).

The analysis in the paper is done based on the condition that the weight functions are calculated in respect to the family of models, generated by the change only of the turbine power in a certain range (0.4÷0.8 p.u.). The step of change of ΔP_{mech} is 0.025 p.u. and is small enough so that there is the confidence that no specific situations are missed. In Fig. 2 are shown the frequency responses of the family open systems G_{EPS}, and in Fig. 3 – the frequency responses of the family of systems closed with AVR and PSS (see Fig. 1). It is interesting to notice how the introduction of AVR and PSS completely changed the behavior of the generator unit.

One should always keep in mind what will be the purpose of the uncertain model he is constructing. In this paper the purpose of the model is to validate that the introduction of unstructured uncertainty represents adequately the real family of models for a range of possible operating point and to check if it gives proper assessment of the robust stability of the system. Also, the other purpose is to check the robust stability when certain AVR and PSS are introduced into the model and to be able to compare the robustness of the system for other

AVR and/or PSS. Having this in mind, the weight functions are calculated in respect to the outputs of the generator itself.

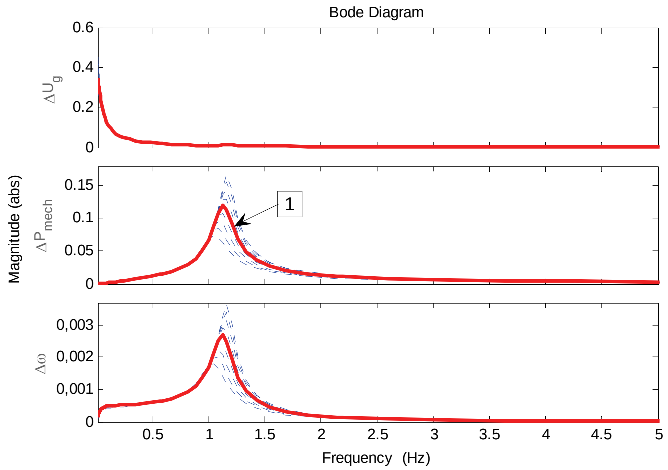

Fig. 2. Frequency response of family open systems G_{EPS} for P_{mech} in the range 0.4÷0.8 p.u. (1 – nominal model for P_{mech} = 0.6 p.u.)

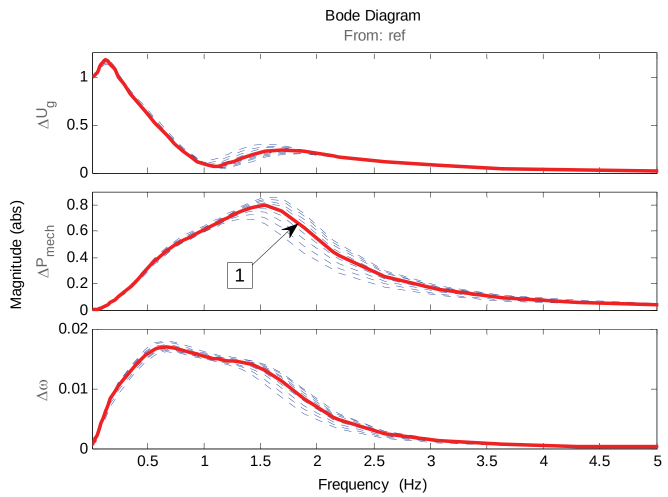

Fig. 3. Frequency response of family closed with AVR and PSS systems, for P_{mech} in the range 0.4÷0.8 p.u. (1 – nominal model for P_{mech} = 0.6 p.u.)

But if one wants for example to synthesize a PSS, the approach to constructing the model should be different. First uncertainty should be introduced only in the channel of the AVR. Its weight function should be calculated, of course, in respect to that channel of the open system (because after all the AVR is fixed and its purpose is to cope with the uncertainties). Only then the AVR is introduced and this way the uncertainty of this channel is "trapped" in the AVR feedback channel. As seen in Fig. 3, the other channels, which the PSS is going to use, change their behavior significantly and this is the uncertainty that the synthesized PSS should deal with. This is why the weight functions of the uncertainties in the channel, which the PSS is going to use, should be calculated in respect to the system closed with the AVR. Only then the uncertainties will be presented correctly for the purpose of synthesis of robust PSS.

An illustration of the above said are the step responses of the family open systems G_{EPS} (Fig. 4) and of the family closed with AVR and PSS systems (Fig. 5). It is interesting how despite the wide range of deviation of P_{mech}, the outputs closed system vary very little.

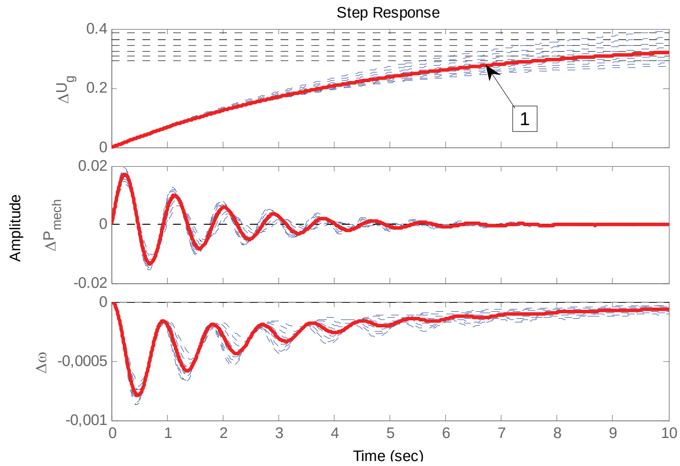

Fig. 4. Step response of family open systems G_{EPS} for P_{mech} in the range 0.4÷0.8 p.u. (1 – nominal model for P_{mech} = 0.6 p.u.)

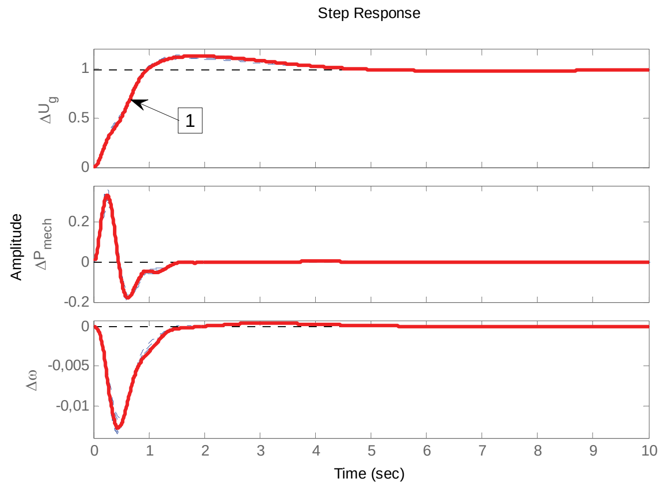

Fig. 5. Step response of family closed with AVR and PSS systems, for P_{mech} in the range 0.4÷0.8 p.u. (1 – nominal model for P_{mech} = 0.6 p.u.)

III. Case Study

A. Choice of nominal model

In this paper is analyzed the influence of different preconditions on the selection of appropriate weight functions. First the effect of the choice of nominal model is studied. Three distinct cases were considered – for nominal was chosen the model corresponding to an operating point, determined by P_{mech} at the upper limit of its supposed deviation range ($P_{mech,1}$ = 0.8 p.u.), at the middle of the range

($P_{mech,2}$ = 0.6 p.u.) and at the lower limit ($P_{mech,3}$ = 0.4 p.u.). The weight functions were calculated according to the well-known expression [1,2] separately for each input-output channel, based on the boundaries of the frequency responses of the family generated models, i.e.

$$\left|W_{m_{P,K}}(j\omega)\right| \geq \frac{\left|G_{P,K}(j\omega)-G_{EPS,nom_{P,K}}(j\omega)\right|}{\left|G_{EPS,nom_{P,K}}(j\omega)\right|} \qquad (1)$$

where indexes p and k represent the outputs and the inputs of the system, G represents the family of generator's models, obtained by the change of P_{mech} in the range 0.4÷0.8 p.u. An interpretation of that expression is that $W_{m_{P,K}}$ holds the biggest relative (to the particular nominal model) variations of G over the frequencies. In Fig. 6 are shown the weight functions for the three different cases of choice of nominal model.

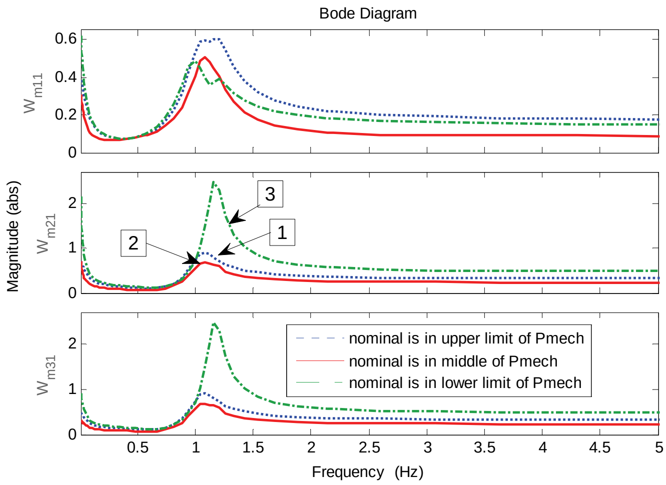

Fig. 6. Weight functions (for each input/output channel) in respect to nominal model for:
1 – $P_{mech,1}$ = 0.8 p.u.; 2 – $P_{mech,2}$ = 0.6 p.u.; 3 – $P_{mech,3}$ = 0.4 p.u.

In the course of generation of the family of models was validated that all open systems G_{EPS}, together with the closed with AVR and PSS systems are stable. It should be mentioned here that G_{EPS} has the particularity that its output do not change independently. In order to account this feature, when building the uncertainty matrix $\mathbf{\Delta}$, one and the same uncertainty block was placed in the main diagonal of the matrix, instead of using different and independently varying uncertainty blocks for each output.

After the formation of the uncertainty models for the different cases of choice of nominal model, the system was closed with the AVR and PSS and its robust stability was checked with MATLAB function robuststab.

The results in Table I clearly show that choice of the nominal model on the limit values of the independently varying parameter leads to more pessimistic assessments of the structured singular value μ and respectively of the robust stability. Even more – in the case of nominal model corresponding to the lower limit of P_{mech}, the uncertain system was assessed as robustly unstable and this is misleading.

TABLE I. ROBUST STABILITY FOR DIFFERENT CHOICES OF NOMINAL MODEL

Nominal mode of the uncertain system for the case of:	Robustly stable uncertain system?	Maximal value of upper limit of μ
$P_{mech,1}$ = 0.8 p.u.	Yes	0.7524
$P_{mech,2}$ = 0.6 p.u.	Yes	0.6674
$P_{mech,3}$ = 0.4 p.u.	**NO**	1.973

These results are basis to recommend the choice of the nominal model for the uncertain system to correspond to value of the varying parameter in the middle of their range instead of the actual nominal operating point of the generator. This is why the rest of the study is carried with nominal model corresponding to P_{mech}=0.6 p.u.

B. Shape of the weight function

The second aspect of the study is the comparison the possibility to represent the uncertainty with different weight functions for each input-output channel or with one and the same for all input-output channels. Two cases for formulation of single weight function are considered. The first one is based on the maximal relative deviation of the maximal singular value of the family of generated models in respect to the maximal singular value of the nominal model, i.e.

$$\left|W_m(j\omega)\right| \geq \bar{\sigma}\left(G(j\omega)-G_{EPS,nom}(j\omega)\right)./\,\bar{\sigma}\left(G_{EPS,nom}(j\omega)\right) \quad (2)$$

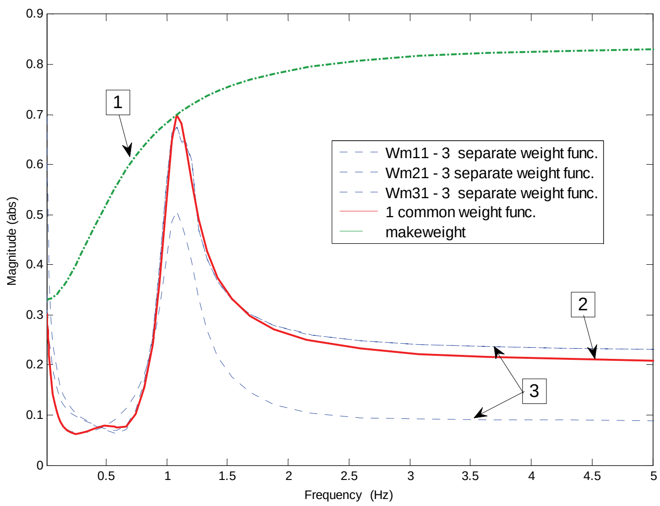

Fig. 7. Calculated weight functions:
1 – single function, common for all input/output channel, calculated by makeweight; 2 – single function, common for all input/output channel, calculated by maximal sigma of the system; 3 – three separate functions (by one for each input/output channel)

The second case is based on the MATLAB function makeweight, often used in the literature. It has the following syntax G = makeweight(dc, crossw, hf) and creates a stable, 1st-order continuous time state-space system G such that the frequency response of G satisfies G(j*0) = dc,

|G(j*crossw)| = 1, and G(j*∞) = hf. It must be that |DC| < 1 < |HF|, or |HF| < 1 < |DC|.

It is calculated in such a way that it encloses the weight function calculated by the maximal singular values. All different weight functions are shown in Fig. 7.

Table II shows the robust stability analysis for the different choices of weight functions. It is obvious that makeweight generates a weight function which with its shape is inappropriate for the problem of uncertainties in an EPS.

TABLE II. ROBUST STABILITY FOR DIFFERENT CHOICES OF WEIGHT FUNCTIONS

Case of choice of weight function:	Robustly stable uncertain system?	Maximal value of upper limit of μ
3 separate weight functions	Yes	0.6674
1 weight function for all input/output channels, calculated by maximal sigma of the system	Yes	0.5915
1 weight function for all input/output channels, calculated by makeweight	**NO**	1.021

The MATLAB function wcgain was used to calculate (for each frequency point) the worst gains on the input-output channels for the 3 separate and 1 common weight functions and was compared with the worst gains of the family of models corresponding to real systems with operating points of P_{mech} in the range 0.4÷0.8 p.u. The results are shown in Figs. 8 and 9. It is clearly seen that both cases enclose the reactions of the real systems meaning the they are both good representation of the family of real models.

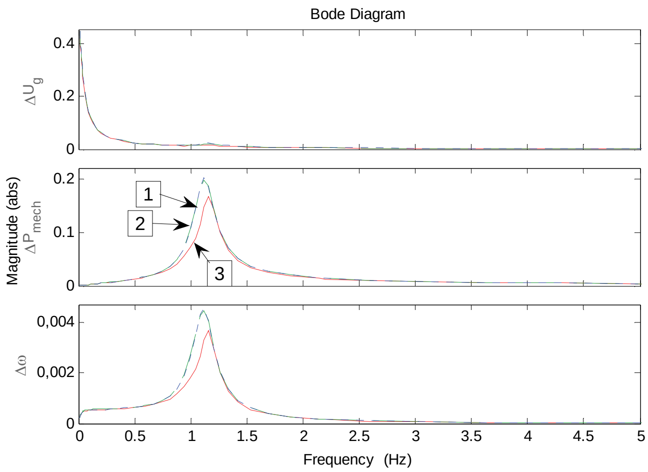

Fig. 8. Worst case gains by frequency points of the open system G_{EPS}:
1 – with single weight function, common for all input/output channel; 2 – with three separate weight functions (by one for each input/output channel); 3 – the limits of the family of real models;

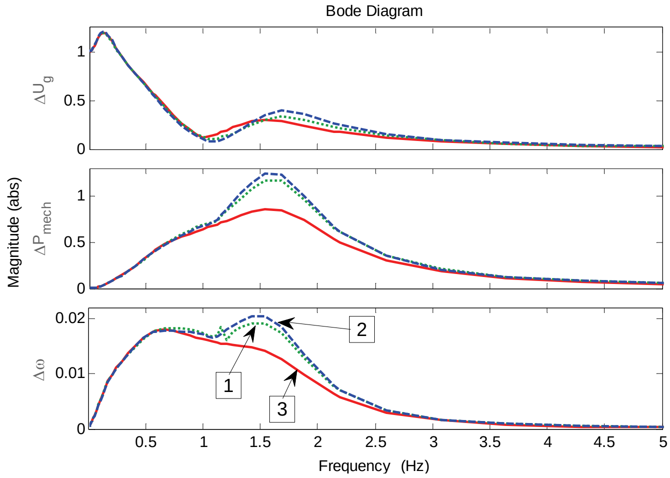

Fig. 9. Worst case gains by frequency points of the closed with AVR and PSS system:
1 – with single weight function, common for all input/output channel; 2 – with three separate weight functions (by one for each input/output channel); 3 – the limits of the family of real models;

IV. CONCLUSION

Having specified a range of change of the independent regime parameters of EPS, it is appropriate to choose the nominal system to correspond to an operating point in the middle of the variation ranges.

The weight functions for modeling unstructured output multiplicative uncertainty should represent the character of the frequency responses of the channels because in the general case there is more than one resonant frequency caused by the interaction of electrical and mechanical processes in EPS. In this sense the use of the MATLAB function makeweight for generation of weight function is not appropriate for modeling uncertainties in EPS.

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