Using $\mathcal{H}_\infty$ synthesis for finding settings of single channel power system stabilizers of synchronous generators

Konstantin Gerasimov[1], Petko Petkov[2] and Krum Gerasimov[3]

Abstract –**This paper presents a methodology for finding settings of single channel power system stabilizers by approximation of the frequency response of the synthesized $\mathcal{H}_\infty$ controller satisfying the requirements for maximal damping of the synchronous generator electromechanical oscillations and minimization of the measurement noise. Test results are presented for a real synchronous generator from the Bulgarian electric power system. The advantages of the proposed methodology are discussed.**

Keywords – **$\mathcal{H}_\infty$ synthesis, power system stabilizer, tuning**

I. INTRODUCTION

Modern power plants are equipped with power system stabilizers (PSS) for damping the electromechanical oscillations of synchronous units. In accordance to their structure we differentiate them as single- and dual-channel. A typical single channel PSS with rotor speed as input signal (PSS1A) [1] is shown in Figure 1.

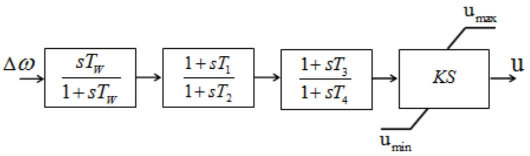

Fig. 1. Block-diagram of PSS1A

In the electric power system (EPS) of Bulgaria mainly single channel PSS are used, with input signal form the equivalent sum of the generator active power (P_e) and rotor speed (ω). This equivalent input signal is obtained after the signals of P_e and ω pass through input filters and then once again through a torsion filter which rejects the torsion oscillations originating from the generator rotor. These PSS are classified as type PSS2A and PSS2B.

The general structure of PSS2A of Alstom is shown in Figure 2. The difference between the different manufacturers' modifications is in the number of the phase-shifting blocks included (and in some elements in the input filters). For example, in Bulgaria there are PSS2A from Alstom with 4 phase-shifting blocks and there are as well PSS2A of ABB with 2 blocks.

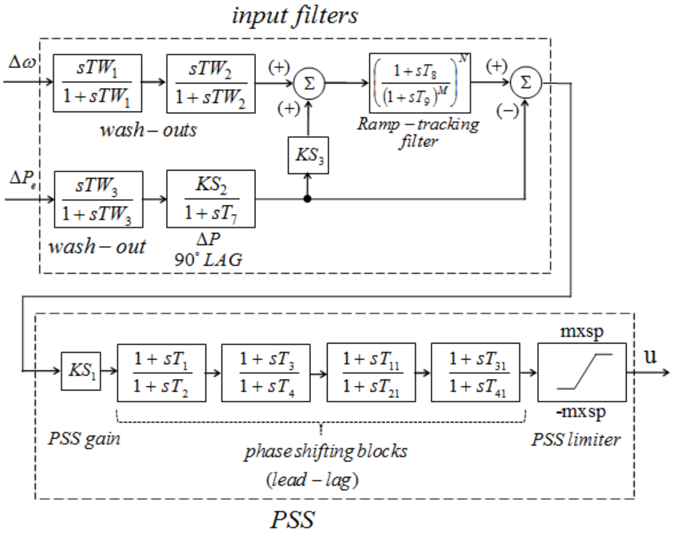

Fig. 2. Block-diagram of Alstom realization of PSS2A

The input filters are tuned in such a way that they do not pass the settled deviations of the regime parameters, and the PSS phase-shifting blocks – to maximally damp the electromechanical oscillations. The settings can be determined by a variety of different methodologies [2-4].

The purpose of this paper is to present a methodology, developed by the authors, for single channel PSS tuning based on $\mathcal{H}_\infty$ synthesis, and to discuss its advantages.

II. METHODOLOGY FOR SINGLE CHANNEL PSS TUNING BASED ON $\mathcal{H}_\infty$ SYNTHESIS

A. Mathematical model

For analysis of the electromechanical oscillations of the motors in EPS a mathematical description linearized around a certain operating point is used. The size of this mathematical description is too big due to the great number of elements in the modern united systems. Because the purpose is to tune a particular PSS of a particular synchronous generator, the authors have developed a methodology for frequency aggregation of the multidimensional EPS mathematical description in respect to the studied generator buses [5,6]. The descriptions results in the following structure:

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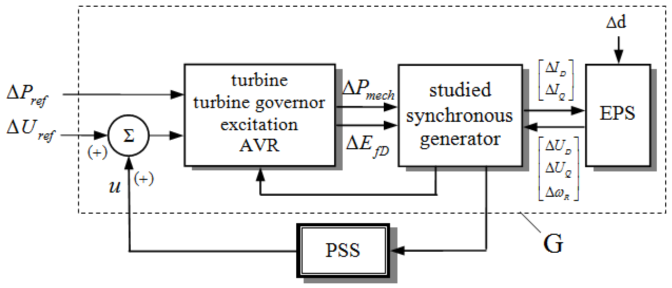

Fig. 3. Block-diagram of the linearized mathematical description for determination of PSS settings of a generator

The mathematical description of the building elements in Figure 3 are obtained according to [2,5,7].

B. $\mathcal{H}_\infty$ synthesis

The general formulation of the $\mathcal{H}_\infty$ control problem can be presented by the block-diagram in Figure 4 [8,9].

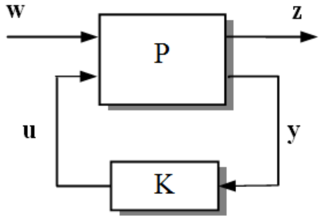

Fig. 4. Block-diagram of $\mathcal{H}_\infty$ control design

In this form the "external" input **w** is the vector of all signals which come into the system and the "error" **z** is the vector of all signals which are necessary to describe the behavior of the closed-loop system. *P* contains the plant transfer matrix *G* and weighting functions which are specific for every synthesis problem. *K* is being synthesized (searched) control function. The standard task for $\mathcal{H}_\infty$ optimal control is to find a stabilizing function *K* which minimizes:

$$\left\|F_l\left(P,K\right)\right\|_\infty = \max_\omega \bar{\sigma}\left(F_l\left(P,K\right)\left(j\omega\right)\right) \quad (1)$$

In MATLAB® this task is solved by the hinfsyn function from Robust Control Design ® 3 toolbox.

The synthesis of control function based on signals is a common approach to MIMO problems for which simultaneously a few different (and usually controversial) goals are required. In this particular problem the following goals are set:

- maximal damping of the electromechanical oscillations manifested in rapid damping of the rotor speed deviation and the generators active power deviations. Thus the generators influence over the rest of the EPS during transient processes will be minimized;
- maximal filtration of the measurement noise. Passing this noise through PSS leads to high frequency oscillations in the excitation circuit and thus the other generator regime parameters. It is even possible that there may be a 50 Hz component in the noise which can result in very troublesome resonance phenomena.

Having in mind the above, the synthesis model in Figure 4 objectifies to the structure in Figure 5:

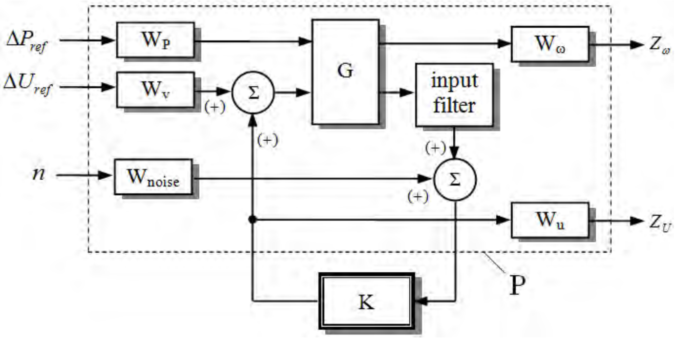

Fig. 5. Block-diagram of the $\mathcal{H}_\infty$ synthesis, based on signals, of stabilizer K

The weighting functions of reference (W_p, W_v) and disturbance (W_{noise}) can be constant or dynamic and describe the relative importance and/or the frequency contents of the inputs. The weighting function W_ω sets the requirements in respect to the degree of damping of the rotor speed, and W_u – the requirements concerning the limitations of the PSS output signal. As seen in Figures 1 and 2 the PSS output is equipped with non-linear limiters.

C. Algorithm

The algorithm for single channel PSS tuning consists of the following steps:

1) Formulation of the mathematical description of the studied generator, as shown in Figure 3;
2) Formulation of weighting functions and of transfer matrix *P*, as shown on the block- diagram in Figure 5;
3) Using the constructed transfer matrix *P* an $\mathcal{H}_\infty$ stabilizer is synthesized by means of the MATLAB® function hinfsyn;
4) Tuning of the fixed-structure single channel PSS in Figure 1 or in Figure 2 so that its frequency response is as close as possible to the frequency response of the mathematically synthesized stabilizer. This is achieved by searching for coincidence, of the phases or of the amplitudes of the frequency response in the frequency range of the electromechanical oscillations, using approximating functions which solve non-linear least square problems.
5) Analysis of the behavior of the tuned PSS. The step and frequency response are recalculated and the fulfillment of the goals, set during the synthesis, is assessed. If the results are unsatisfactory, first a return to step 4 is made and the structure and parameters of approximation are varied. If even this cannot lead to satisfactory results a return to step 2 is made where the weight functions have to be reconsidered and from there on the process repeats.
6) Construction of model with uncertainties for the purpose of the robust analysis. This can be done with the help of the developed by the authors software tool **RobustPSS** [10], allowing modeling of structured uncertainty, presented in state space, and of unstructured

uncertainty, presented in the frequency domain, which are caused by the uncertainties in the generator load and the system operating point.

7) Analysis of the robust stability. It is done by means of the MATLAB® function `robuststab`.

III. TEST RESULTS

The proposed algorithm is tested for tuning Alstom PSS2A of a real 370 MW synchronous generator from a Bulgarian thermal power plant. The frequency equivalentation of the EPS in respect to the generator bus is reduced to order of 20. The weighting functions used in the synthesis are as follows:

$$W_p = 1; \qquad W_v = 1;$$

$$W_{noise} = \frac{0.0521\cdot s^3 + 9.48\cdot s^2 + 1293\cdot s + 7.429\cdot 10^4}{s^3 + 1696\cdot s^2 + 2.147\cdot 10^5\cdot s + 9.018\cdot 10^7};$$

$$W_u = 0.8; \qquad W_w = \frac{46.17\cdot s^2 + 41.5\cdot s + 1.442}{s^2 + 0.1198\cdot s + 0.0003}$$

The $\mathcal{H}_\infty$ synthesis is carried out under the assumption that the input filters are tuned well because it is a common practice, due to subjective reasons, that it is not allowable to change the settings of the input filters. In this particular case the settings are as follows: $ks_3 = 1$ p.u.; $TW_1 = 7$ s; $TW_2 = 7$ s; $TW_3 = 7$ s; $ks_2 = 0.86$ p.u.; $T_7 = 7$ s; $T_8 = 0.6$ s; $T_9 = 0.15$ s; M = 4; N = 1.

Under these conditions the $\mathcal{H}_\infty$ synthesized controller has frequency response shown in Figures 6 and 7. In Figure 6 it is compared with PSS2A tuned by approximation of the amplitude and in Figure 7 – tuned by approximation of the phase. One should not forget that the fixed-structure PSS settings can vary only in certain ranges. In this case T_1, T_3, T_{11}, and T_{31} = 0 ÷ 10 s, while T_2, T_4, T_{21}, and T_{41} = 0.015 ÷ 3 s. Due to subjective reasons, the authors have chosen ks_1 to vary between 5 and 20 p.u.

It is clear that in this particular case the approximation by amplitude gives better results and this is why it will be used. The obtained in this way settings are: $ks_1 = 5$ p.u.; $T_1 = 0.0951$ s; $T_2 = 0.0367$ s; $T_3 = 0.6686$ s; $T_4 = 0.0367$ s; $T_{11} = 0.0967$ s; $T_{21} = 0.0367$ s; $T_{31} = 0$ s; $T_{41} = 0.0664$ s.

The gain ks_1 is relatively small and we can afford to increase it 1.8 times without the PSS output signal to reach the PSS output signal limitation (see Figure 8).

In general we could fine adjust the gain ks_1 because it doesn't affect the PSS phase compensation and exactly it is crucial for the right operation of PSS. But by changing ks_1 we change the degree of damping. For this reason from here on the presented results are for $ks_1 = 9$ p.u. and the effect can be clearly seen in Figure 9. It shows a significant damping of the rotor speed oscillations when the tuned PSS is switched on. A significant damping of the active power oscillations is achieved as well and this can be seen in Figures 10 and 11.

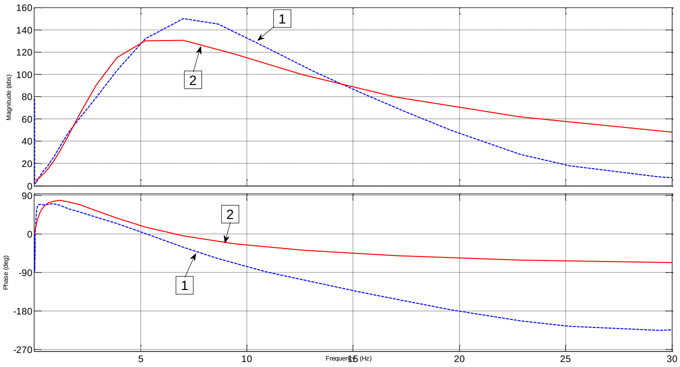

Fig. 6. Frequency response of: 1 – the $\mathcal{H}_\infty$ synthesized controller 2 –PSS2A, tuned by approximation of the **amplitude**

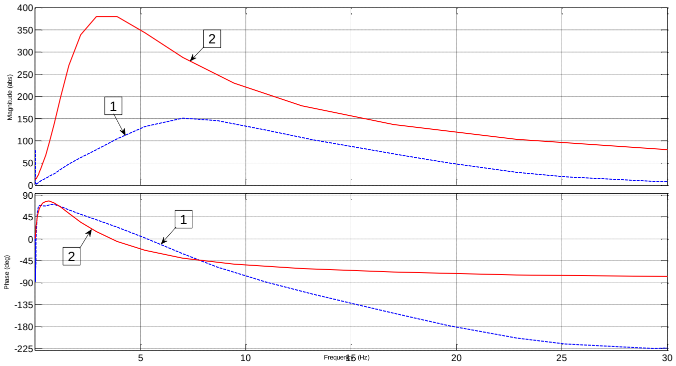

Fig. 7. Frequency response of: 1 – the $\mathcal{H}_\infty$ synthesized controller 2 –PSS2A, tuned by approximation of the **phase**

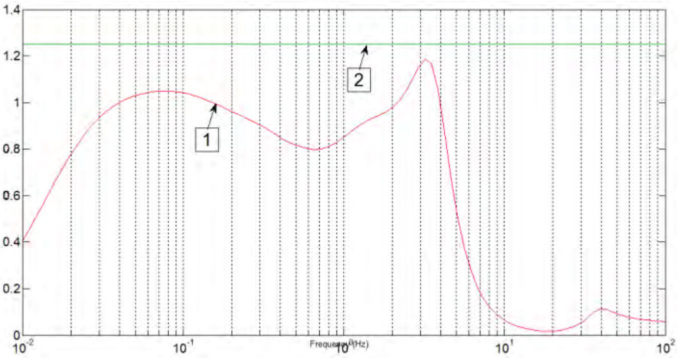

Fig. 8. Frequency response of PSS2A (1), tuned by approximation of the amplitude and $ks_1 = 9$ p.u., compared to the PSS output signal limitation (2)

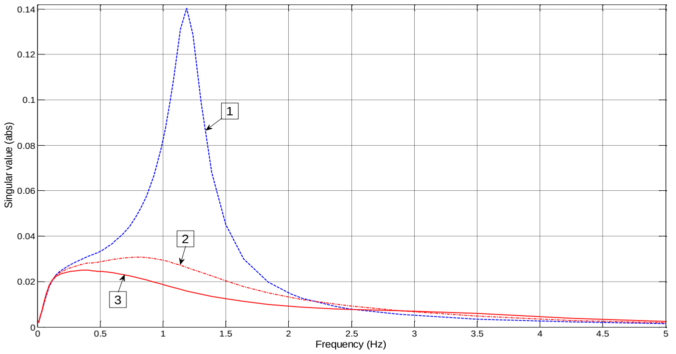

Fig. 9. Maximal singular values of transfer matrix from all inputs to Δω of the generator: 1 – without PSS; 2 – with PSS2A ($ks_1 = 5$ p.u.); 3 – with PSS2A ($ks_1 = 9$ p.u.)

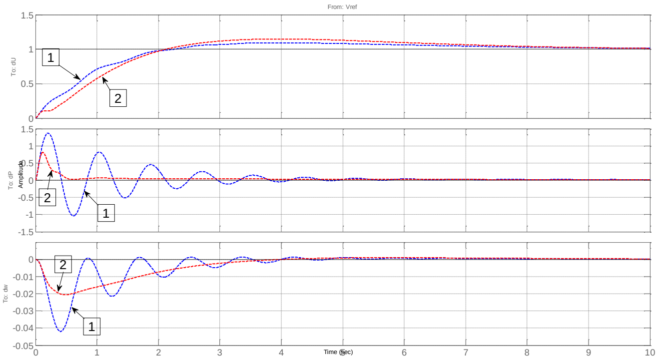

Fig. 10. Step response of the nominal generator model for step change of V_{ref}: 1 – without PSS; 2 – with PSS2A (ks_1 = 9 p.u.)

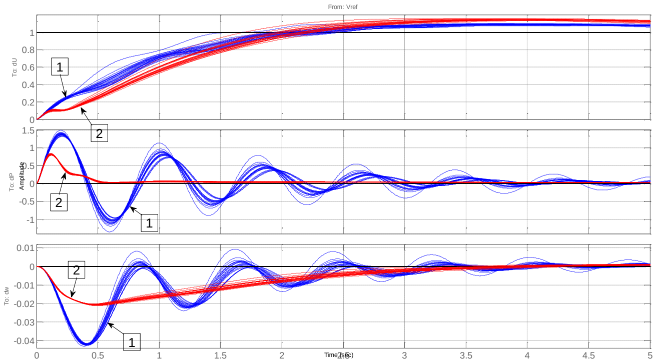

Fig. 11. Step response of the generator, modeled with uncertainties, for step change of V_{ref}:
1 – without PSS; 2 – with PSS2A (ks_1 = 9 p.u.)

The uncertain model used for robust stability check consists of output unstructured multiplicative uncertainty of 10% in the EPS model and structured uncertainty in the generating unit state space realization describing change of the active power in its whole allowable range. In Figure 12 is shown that a sufficient robust stability margin of 137 % is achieved.

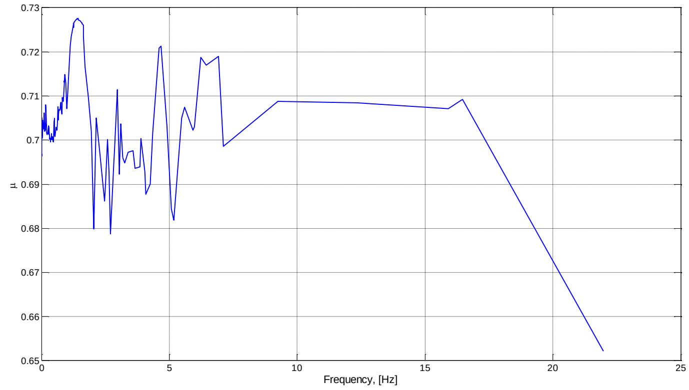

Fig. 12. Upper bound on the mixed structural singular value μ of the generator with PSS2A with ks_1 = 9 p.u.

IV. CONCLUSION

As a conclusion it can be summarized that the proposed algorithm has as main advantage that given a particular *fixed structure PSS*, one can tune it considering *simultaneously* the following limiting requirements:

1) ensure quality of the transient processes (better damping of the generator electromechanical oscillations);
2) the PSS output signal doesn’t reach its limitation;
3) suppresses the measurement noise.

ACKNOWLEDGEMENT

The authors would like to express their appreciation of eng. Venci Zahov (head of division “System analyses & Transmission Planning” in National Dispatching Center by the Bulgarian Electricity System Operator) for his generous and active collaboration.

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