Functionalities Extension of the NASAVR Software For Small-Signal Stability of Electric Power Systems

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Abstract – **This paper presents the functionalities extension of the NASAVR software tool for calculation of optimal settings of automatic voltage regulators and power system stabilizers of synchronous generators. The software tool was developed for NEK EAD (the National Electric Company of Bulgaria) by a team of experts from Technical University of Varna, headed by Prof. Dr.Sc. Eng Math. Krum Kostov Gerasimov.**

Keywords – **Electric power systems, synchronous generator, small-signal stability, automatic voltage regulators, power system stabilizers.**

I. INTRODUCTION

In May 2013 the electric power system (EPS) of Bulgaria, owned then by the National Electric Company (NEK EAD) of Bulgaria, became a full member of the Union for the Coordination of the Transmission of Electricity (UCTE) as part of the second synchronous zone. After the resynchronization between the first and the second synchronous zones in October 2004, the EPS of Bulgaria operates synchronously with UCTE. The primary obligation of the Bulgarian EPS is maintaining highly efficient and quality synchronous operation with UCTE. Therefore certain criteria had to be fulfilled such as: maintaining the system frequency within narrow limits, damping low-frequency local and inter-area electromechanical oscillations and their corresponding power oscillations. A number of measures for improving the quality of the synchronous operations were made during the preparation process before the interconnection of the Bulgarian EPS to UCTE. One of the most important measures was the rehabilitation of the electric power plants. The automatic voltage regulators (AVR) were modernized with new ones, equipped with power system stabilizers (PSS). The interconnection of the Bulgarian EPS with the UCTE and the negotiations for interconnection of Turkey afterwards, required the extension of the simulation model. Table I presents the model size before (old model) and after (new model) the interconnection of Turkey.

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Meanwhile, NEK started using the PSS®E software for solving power flow and time-domain simulations.

TABLE I
SIMULATION MODEL SIZE

Elements	Old model	New model
Buses	1056	5176
Generators	352	1633
AVR	218	954
PSS	27	124
Transformers	441	1495
Lines	1042	5749
Loads	916	3255

This paper briefly introduces the basic principles of the NASAVR software tool and the functionalities of the new version. The presented examples illustrate the main software features.

II. NASAVR PRODUCT PRESENTATION

A. General overview

The development of the software tool for calculation of the parameters of systems for automatic voltage regulation and power system stabilizers NASAVR [2] was contracted by NEK EAD to a team of experts from Technical University of Varna, headed by Prof. Dr. Sc. Eng Math. Krum Kostov Gerasimov, and has been successfully implemented at NEK EAD.

Fig. 1 presents its generalized structures.

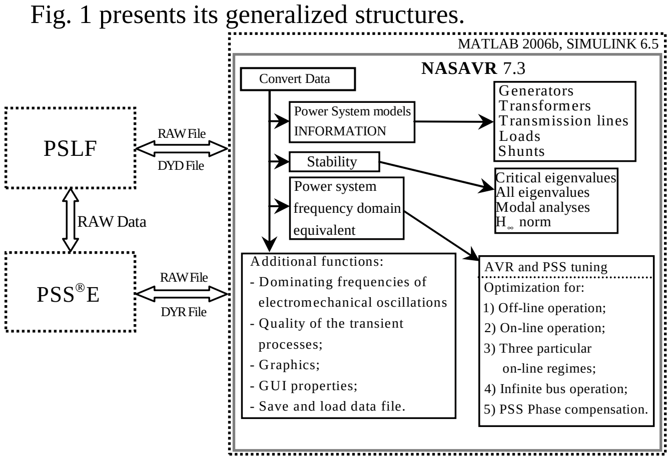

Fig. 1. General structure of the software tool NASAVR ver. 7.3

In the first version of NASAVR are implemented the following features:

- Import of raw data for the analyzed EPS from the database of the software GE PSLF 13.2;
- Systematic representation of the data for the analyzed EPS according to element type, its operation condition

(switched on or off), its type of modeling in NASAVR, or according to the available inputs in the EPS;
- Assessment of the small-signal stability of the analyzed steady state and identification of the dominant frequencies in the electromechanical oscillations;
- Calculation of the critical eigenvalues of the EPS under small disturbances;
- Application of standard or accelerated procedure for calculation of eigenvalues or eigenvectors;
- Assessment of the quality of the transient processes in EPS under small disturbances, based on the eigenvalues;
- Frequency equivalentation of the EPS by aggregation of its detailed mathematical description in the frequency domain in respect to the buses of the generators which are going to be tuned;
- Determination of the AVR and PSS settings in respect to the criteria for preservation of the small-signal stability and the quality of the transient processes for one or three operating regimes at the same time;
- Calculation of the frequency and step response of the synchronous generators in order to evaluate the quality of the transient processes;
- Capability to account for the influence of real deviations of load and voltage at the buses of the analyzed generator at the process of optimization of AVR and PSS parameters.

B. Import of input data from other programs (PSLF 16.04 and PSS®E 30.2)

In order to make NASAVR more flexible, its source code was altered so that it can import data from the latest versions of the programs for power flow and dynamic stability analysis PSLF 16.04 and PSS®E 30.2. This was very important since most of the data exchanged in international projects is in PSS®E format. NASAVR recognizes the data format and reads it without the use of intermediate conversion software. This significantly speeds up the procedure for extraction of the necessary data from files reaching 50 000 lines of code.

C. Expansion of the model database

Another advantage of NASAVR is the variety of models implemented in it. As part of the modernization of power plants in the Bulgarian EPS were installed new AVR and PSS systems of different manufacturers like ABB, SIEMENS, ASLTOM and VATECH. This required the update of the model database. It should be noted that NASAVR works with mathematical descriptions linearized around a certain operating point and this means that direct implementation of the regulating systems models cannot be implemented directly but require linearization. Everything is based on standardized models [4], taking into account some specific features of the models in PSLF and PSS®E [5,6].

The latest version of NASAVR is capable of recognizing the following models:

Generator models *for an EPS model, created in***:**

- *PSLF*: gencls, genrou, gensal;
- *PSS®E*: gencls, genroe, genrou, gensae, gensal.

Excitation system models *for an EPS model, created in***:**

- *PSLF*: esac2a, esac3a, esac7b, exac1, exac1a, exac2, exac3, exac3a, exac4, exac6a, exac8b, exbbc, exdc1, exdc2, exdc2a, exdc4, exeli, exst1, exst2, exst2a, exst3, exst3a, exst4b, ieeet1, rexs, sexs, esdc1a, esdc2a, esdc3a, esst5b, esst6b, esst7b, exeli2;
- *PSS®E*: esac1a, esac2a, esac3a, esac4a, esac5a, esac6a, esac8b, esdc1a, esdc2a, esst1a, esst2a, esst3a, esst4b, ex2000, exac1, exac1a, exac2, exac3, exac4, exbas, exdc2, exeli, expic1, exst1, exst2, exst2a, exst3, ieeet1, ieeet2, ieeet3, ieeet4, ieeet5, ieeex1, ieeex2, ieeex3, ieeex4, ieet1a, ieet1b, ieet5a, ieex2a, sexs, urst5t, bbsex1, celin, emac1t, esurry, ivoex, urhidt.

PSS models *for an EPS model, created in***:**

- *PSLF*: ieeest, pss2a, wsccst, pss2b, psssh;
- *PSS®E*: iee2st, ieeest, pss2a, ptist1, ptist3, st2cut, stab1, stab2a, stab3, stab4, ivost, stabni, ostb2t, ostb5t.

Additionally are model PSS of the following manufacturers: Elektrosila (Russia), kmu-siemens, gec alstom. also, there are models of pss type pss4b [8], mreck4 and mpss1a.

Turbine and turbine governors models:

- *PSLF*: gast, hygov, ieeeg1, ieeeg3, tgov1, tgov3;
- *PSS®E*: gast, hygov, ieeeg1, ieeeg3, tgov1, tgov3.

Totally, the latest version of NASAVR implements 123 models, compared to the 20 models at the initial version of the software.

D. New features

Thanks to the years of scientific research of the team which developed the software and the gained experience since its implementation, an expansion of the software features as well was made possible. Hereby are presented briefly only the most important one, concerning the analysis of the EPS small-signal stability and the determination of optimal settings of the AVR and PSS. These are:

- Optimization of the parameters of PSS by application of methods for phase compensation by momentum and by voltage in order to improve the damping of the low-frequency inter-area oscillations;

- Grouping of the synchronous units according to the phases of the oscillations they participate in and calculation of their damping degree;

- Capability to calculate the frequency response of a synchronous unit for input control and disturbing signals for all regime parameters;

- Generalized assessment of the quality of the transient processes of the analyzed generator or of the EPS as a whole by calculation of the H_∞ norm of the transfer matrix from the input signals to the mechanical speeds of the rotors [1,3,7];

- Incorporation of module which simulates measurement noise (available in practice) and of an algorithm for assessment its gain and influence when it passes through the regulating and stabilizing utilities;

- The calculated new settings of the AVR and PSS can be tested for 30 different operating points, chosen in advance in respect to the generator’s load diagram.

III. TEST AND IMPLEMENTATION OF NASAVR

In order to concentrate the attention on a specified synchronous unit during the analysis, the general mathematical model can be reordered into the structure shown in Fig. 2.

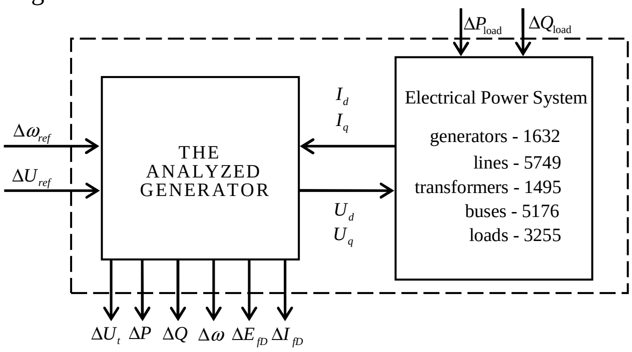

Fig. 2. Block diagram of the mathematical model, used for analysis of a specified synchronous unit

For verification of the composed model is used a recorded step response of the generator output active power, for a step change of reference of the automatic voltage regulator (Fig. 4). The composed mathematical model is the used to simulate the step response for the same conditions and for the corresponding operating state before the disturbance (Fig. 3). It is clearly seen that practically, at the initial stages of the transient process, there is overlapping of the times and magnitudes. At the next stages also practically there is no significant deviation of the main component. There are some deviations in the other components which are caused by a disturbing signal. Because it is accidental in nature, it cannot be reproduced exactly at the simulation and hence the deviations.

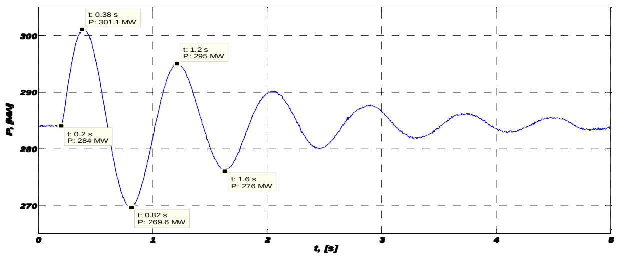

Fig. 3. Step response of the generator output active power, calculated with the developed simulation model, for a step change of **+3%** of U_{ref} and with PSS switched off

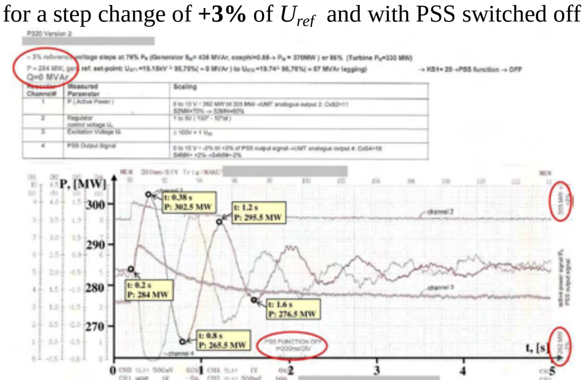

Fig. 4. Recorded step response of the generator output active power, for a step change of **+3%** of U_{ref} and with PSS switched off

In Fig. 5 is shown the H_∞ norm of the transfer matrix of the interconnected system generator–EPS. The generator is loaded with 213 MW active power and with 17.15 MVAr reactive power. At its buses is measured voltage of 15.55 kV (this operating state is valid for all the results shown in figures from Fig. 5 to Fig. 9). One can clearly differentiate the influence of PSS on the local frequencies of oscillation (around 1Hz), when it is switched on. Also, appropriate settings of the PSS [7] could make it damp inter-area oscillations as well (see the red curve around 0,1Hz). Inappropriate settings though could amplify them (compare the blue curve around 0,1Hz in respect to the red and green ones).

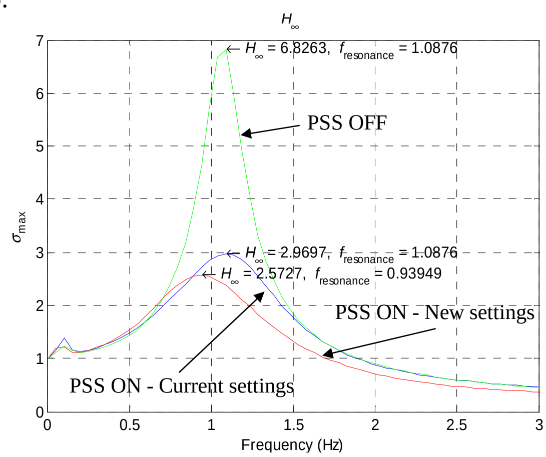

Fig. 5. H_∞ norm of the transfer matrix from ΔU_{ref} to all output parameters of the generator

The frequency response from a disturbance in the voltage regulator reference ΔU_{ref} to the deviations of the bus voltage (ΔU), active power (ΔP) and rotor speed ($\Delta\omega$) gives information about the influence of the PSS settings to the synchronous unit.

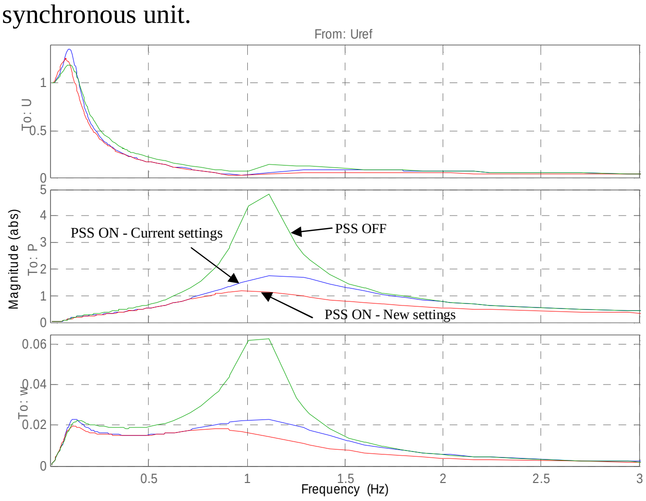

Fig. 8. Frequency response for a disturbance in the voltage regulator reference ΔU_{ref} and the outputs ΔU, ΔP and $\Delta\omega$

The decreased more than twice H_∞ norm for the case when PSS is enabled (see Fig. 5) means improved quality of the transient processes. As confirmation of this fact are shown the results from the step responses of the analyzed generator (Fig. 9). It can be clearly seen, that the measurement noise of the voltage regulator output (ΔE_{fd}) is not passed through to the generator's output regime parameters (ΔU, ΔP, $\Delta\omega$).

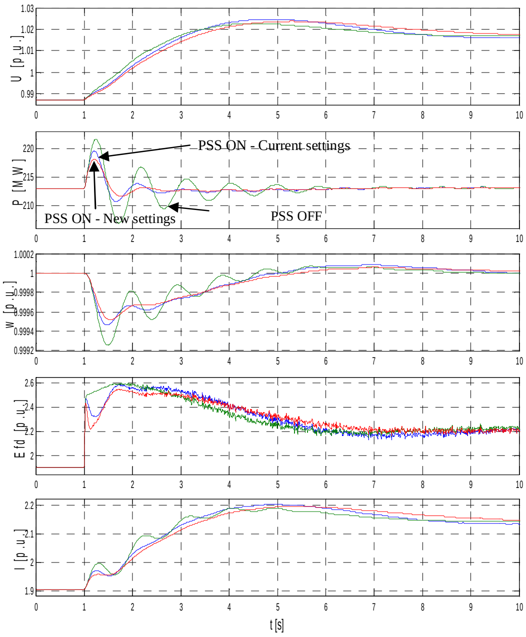

Fig. 9. Step response (with noise) of ΔU, ΔP, $\Delta \omega$, ΔE_{fd} and ΔI_f for a step change of ΔU_{ref} = +3%

Due to the dynamic structure of the EPS and its operating state, it is necessary that calculated appropriate settings should be checked by a variance of calculation for many enough (30) operating points of the analyzed synchronous generator, from different zones of its load diagram (as shown in Fig. 10)

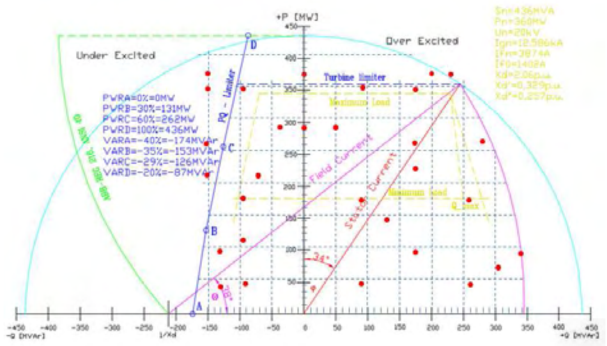

Fig. 10. Example load diagram with specified operating points

The results from the calculated chosen possible operating points, in the form of step responses for the same conditions as the ones from Fig. 9, are shown in Fig. 11.

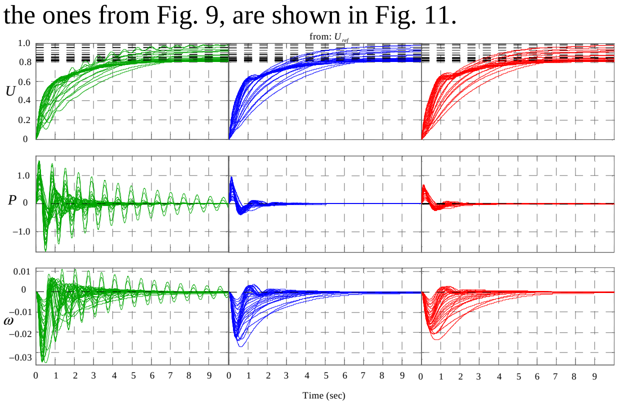

Fig. 11. Family of step response, based on the different operating points from the load diagram of the generator

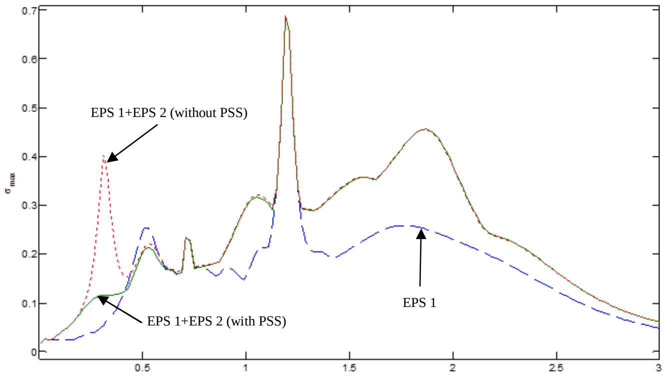

Fig. 12. Maximal singular values of the transfer matrix of two EPS and their interconnection

IV. Conclusion

The presented software tool NASAVR for calculation of the parameters of automatic voltage regulators and power system stabilizers of synchronous generators enable the user to conduct thorough analysis of the small-signal stability of large electric power systems. Proof of its build qualities are the finalized successfully projects for calculation of appropriate PSS settings in main Bulgarian power plants. Also, the team, which developed the software, participated in the calculation of the PSS settings in 5 Turkish power plants regarding the interconnection of the Turkish EPS to the interconnected European EPS ENTSO-E.

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