Determination of Optimal Parameters of PSS Using the Identified Model

Mato Miskovic*, Marija Mirosevic **, Ivan Miskovic ***

*HEP Hydro Area Dubrovnik, Dubrovnik, Dr A. Starčevića 7

** University of Dubrovnik, Ćira Carića 4 20000 Dubrovnik

***Končar KET Zagreb, Falerovo šetalište bb 11000 Zagreb

mato.miskovic@hep.hr, marija.mirosecic@unidu.hr, miskovic.ivan@gmail.com

‡ Corresponding Author; Second Author, Postal address, Tel: +90 312 123 4567,

Fax: +90 312 123 4567,corresponding@affl.edu

Received: 18.08.2015 Accepted:10.10.2015

Abstract- The paper describes the procedure for parameter tuning of the power system stabilizer, as part of the structure of the automatic voltage regulator of synchronous generator AVR. Parameter tuning is based on a method that uses a mathematical model of synchronous generator on the power system. The parameters of the mathematical model of synchronous generator are determined by identification. Application of the identified mathematical model defines the function of dependence of the characteristics of the voltage regulator of the synchronous generator to the parameters of the controller. Developed method for parameter tuning is tested on the real laboratory system.

Keywords Synchronous generator, automatic voltage control, power system stabiliser

1. Introduction

Electromechanical oscillations of synchronous generator which is connected to the power system can reduce stability in operation. These oscillations can be significantly damped by extending the automatic voltage regulator (AVR) with power system stabilizer (PSS).

Determining the values of the parameters settings of the PSS is very complex procedure due to the nonlinear characteristics of a synchronous generator and the power system.

Taking this all into account, the authors have attempted to develop a process of identifying of the mathematical model of synchronous generator in operate on the power system with the aim to improve the procedure of setting PSS. Identification procedure has been developed taking into account the requirement for fast and stable convergence of the numerical procedure, and model that are identified must have required accuracy.

Determination value of parameters settings PSS, is based on determining the optimum operating point of the sensitivity function of eigenvalues of the modelled system. The mathematical model of the system includes: a synchronous generator, power system, automatic voltage regulator and PSS. The function of the sensitivity of the eigenvalues of the system was based on numerical procedure.

Developing and testing procedures will be carried out on a laboratory model of a synchronous generator. Synthesis of digital regulator and measurement system for the identification and testing will be performed with module xPC in Matlab Simulink

2. Model of Synchronous generator on the power grid

Mathematical model of the synchronous generator is presented in [1]. Basic equations of the linearized 3rd order model of synchronous generator in state space matrix form are:

$$\begin{bmatrix} \dot{\Delta\psi_f} \\ \dot{\Delta\omega} \\ \dot{\Delta\delta} \\ \dot{\Delta V_f} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & 0 \\ 0 & A_{32} & 0 & 0 \\ A_{41} & A_{42} & A_{43} & A_{44} \end{bmatrix} \cdot \begin{bmatrix} \Delta\psi_f \\ \Delta\omega \\ \Delta\delta \\ \Delta V_f \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ B_4 \end{bmatrix} \cdot \Delta V_{ref} \quad (1)$$

where: $\Delta\psi_f$ - excitation magnetic flux, $\Delta\omega$ angular velocity, $\Delta\delta$ angular load and ΔV_f excitation voltage.

Model outputs are generator voltage ΔV, angular velocity differential $\Delta\omega$ and active power differential ΔP. Regulator output is generator voltage, with angular velocity and generator power as PSS control inputs

2.1. Identification

. A procedure of direct identification of the state-space matrix coefficients is used in the paper. Two models are formed in order to achieve better identification accuracy and speed up the numerical calculations.

To obtain output variables and output matrix is formed (2).

$$\begin{bmatrix} \Delta V \\ \Delta\omega \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\psi_f \\ \Delta\omega \\ \Delta\delta \\ \Delta V_f \end{bmatrix} \quad (2)$$

To determine output variables ΔV and ΔP using mathematical model in (1) output matrix is formed:

$$\begin{bmatrix} \Delta V \\ \Delta P \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \end{bmatrix} \begin{bmatrix} \Delta\psi_f \\ \Delta\omega \\ \Delta\delta \\ \Delta V_f \end{bmatrix} \quad (3)$$

Relations (1), (2) and (3) are define all system variables used in design of AVR with PSS. Identification procedure directly determines state-space matrix coefficients in relations (1), (2) and (3).

Mathematical model parameters of synchronous generator are identified by applying the Kalman filter [3, 4 and 5]. The parameters of the mathematical model are determined by iteration method in which measured output values on the system being identified are used as algorithm inputs.

Main relations of the Kalman algorithm are

$$K = P(k)\cdot H(k)\cdot\left[\eta(k)\cdot\mathbf{I} + H(k)^{\mathrm{T}}\cdot\mathbf{P}(k)\cdot H(k)\right]^{-1} \quad (4)$$

$$\theta(k) = \theta(k-1) + K\cdot\left[\mathbf{y}_{\mathrm{m}}(k) - \mathbf{y}(k)\right] \quad (5)$$

$$\mathbf{P}(k+1) = \mathbf{P}(k) - K\cdot H(k)^{\mathrm{T}}\mathbf{P}(k) + \mathbf{Q}(k) \quad (6)$$

To determine the Kalman gain in (4), matrix of partial derivatives of model output variables over model parameters $H(k) = \frac{\mathrm{d}\,\mathbf{y}(k)}{\mathrm{d}\,\theta(k)}$ is used. New values of $\theta(k)$ are determined using relation (5), where the parameters value are adjusted by difference of measured and model values $\mathbf{y}_{\mathrm{m}}(k) - \mathbf{y}(k)$. Error covariance matrix is calculated using relation (6). Values of covariance matrix coefficients P (k + 1) are determined in order to be used in the next step. Matrix P (k) coefficients are determined by the efficiency of identification through Kalman gain K, which should be reduced to a negligible amount over successful identification. The value of the matrix P (k) is corrected by a diagonal matrix Q (k), while the values of matrix Q (k) are set arbitrarily. Intentional introduction of errors in the matrix P (k) reduces possibility of local minima results. Kalman identification procedure (4) is comprised of prediction and correction steps. Stability and convergence rate is controlled by setting values of matrix $\mathbf{Q}(k)$ and training coefficient $\eta(k)$.

Efficiency of identification procedure is improved using multi-streaming. In each identification step N consecutive measurement records are used to calculate new values of parameter.

To use multi-streaming matrix dimensions in (4), (5) and (6) need to be adjusted. Vectors and matrices dimensions in multi-streaming procedure are based on the number of input and output values N used in one step, and on the number of output values M of the mathematical model. Vector of modelled and measured outputs is defined as $y_{m[N,M]}$,. Covariance matrix $P(k)_{[M,M]}$, $H(k)_{[N,N\cdot M]}$ is partial derivations matrix, with gain matrix in multi-streaming procedure defined as $K(k)_{[N,M]}$.

To identify mathematical model of synchronous generator (1), vectors of measured and model values of the model being identified, and N_{2y} as the number of coefficients in matrix of measured values in (5). Identification of mathematical model is performed in two steps. In step 1 coefficients of state matrix A, input matrix B and output matrix C are determined, according to (1) and (2). Identification is performed using data obtained from measurements of generator connected to the grid ($y_m = \left[\Delta V\ \Delta\omega\right]^T$).

In step 2 coefficients of state matrix A, input matrix B and output matrix C are determined, according to (3). Identification is performed using data obtained from measurements of generator connected to the grid ($y_m = \left[\Delta V\ \Delta P\right]^T$). To reduce computation time, initial coefficients of matrices A and B are determined from step 1. The coefficients for all matrices of mathematical model (1) are directly determined from identification.

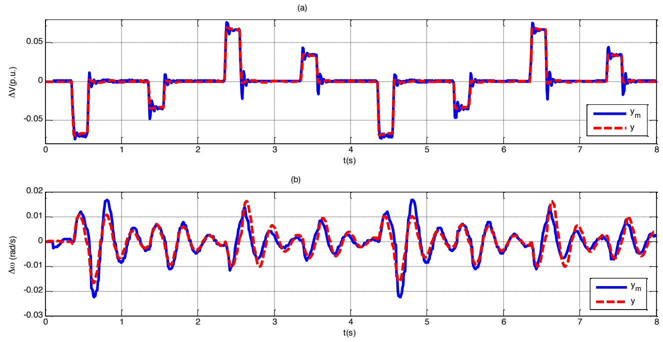

Fig. 1. Comparative plots of generator voltage ΔV and angular velocity $\Delta\omega$, obtained from measurements and simulated using identified model . Measured values are marked with y_m, while the values obtained by applying the identified models marked with y .

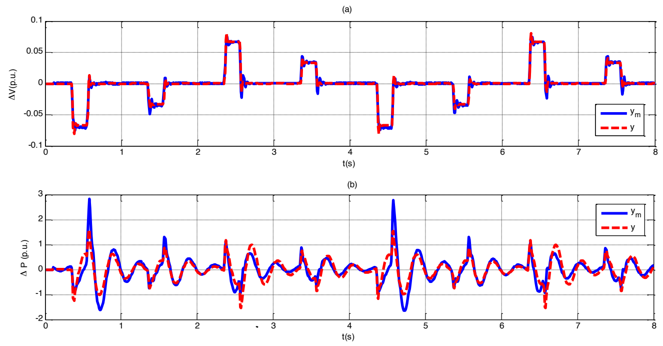

Fig. 2.. Comparative plots of generator voltage ΔV and generator power ΔP, obtained from measurements and simulated using identified model. Measured values are marked with y_m, while the values obtained by applying the identified models marked with y .

In Fig. 1 results of mathematical model identification of synchronous generator (1) and (2) are shown. Measured values are obtained from actual system. A square waveform with 0.2s duration was applied to the voltage reference input of the excitation system. Random values were used for initial model coefficients in (1) and (2).

In Fig. 2 results of mathematical model identification of synchronous generator (1) and (3) are shown. Measurements were performed in same setting as in the previous case. Random values were used for initial model coefficients in (1) and (2). In both cases, identification took 1000 steps to complete.

In Fig. 3 result of mathematical model identification of synchronous generator is shown. Matrix coefficients in (1) and (3) are identified. Output vector $y_m = \left[\Delta V \ \Delta P\right]^T$ is obtained from measurements. In Fig. 3a and 3b measured response and simulation response of identified model are presented.

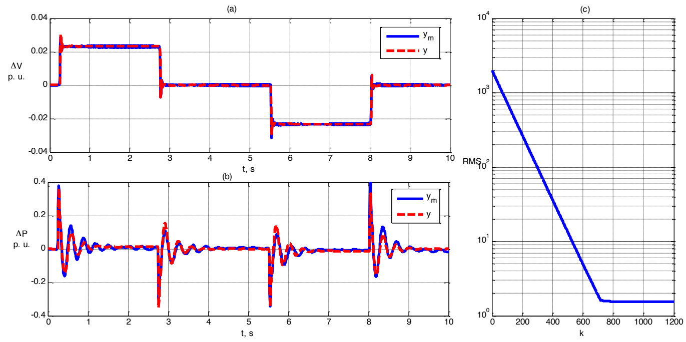

Fig. 3. Identification result for mathematical model of synchronous generator. Measured values are marked with y_m, while the values obtained by applying the identified models marked with y .

Figure 3c shows identification progress, where $RMS = \left[\mathbf{y}_m(k) - \mathbf{y}(k)\right]^T \cdot \left[\mathbf{y}_m(k) - \mathbf{y}(k)\right]$ represents scalar product of model output error. Identification process is stable, with convergence achieved in approximately 700 steps.

3. PSS parameter tuning

Block diagram of mathematical model of the power system stabilizer is shown in Fig. 4. Model inputs are angular velocity differential $\Delta\omega$ and generator power differential ΔP .

The PSS is essentially comprised of two compensation loops ($\Delta\omega$ and ΔP) which can be tuned separately.

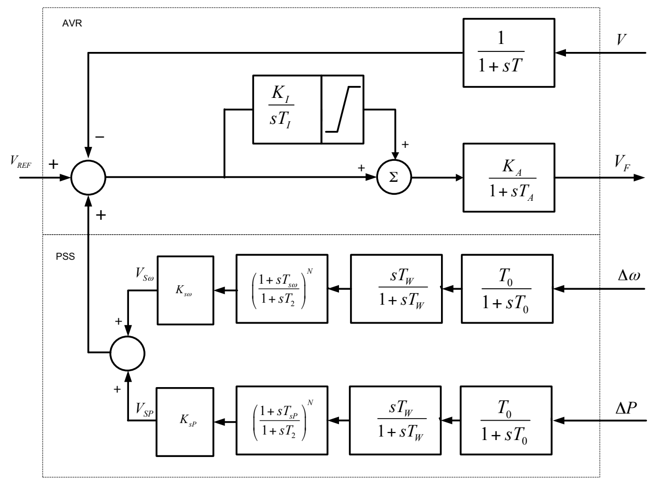

Fig. 4. Block diagram of AVR and PSS.

To tune PSS parameters it is necessary to form a mathematical model of synchronous generator with voltage regulator and PSS. From (1), (2), and (3) follows:

$$\begin{bmatrix}\dot{V}_{s2}\\ \dot{V}_{s1}\\ \dot{V}_{s}\end{bmatrix}=\begin{bmatrix}-\frac{1}{T_{s0}} & 0 & 0\\ \frac{1}{T_{s2}}-\frac{T_{s1}}{T_{s2}}\frac{1}{T_{s0}} & -\frac{1}{T_{s2}} & 0\\ \left(\frac{1}{T_{s2}}-\frac{T_{s1}}{T_{s2}}\right)\frac{T_{s1}}{T_{s2}} & -\frac{1}{T_{s4}}\frac{T_{s1}}{T_{s2}}\frac{1}{T_{s2}} & -\frac{1}{T_{s4}}\end{bmatrix}\begin{bmatrix}V_{s2}\\ V_{s1}\\ V_{s}\end{bmatrix}+\begin{bmatrix}\frac{K_s}{T_{s0}}\\ \frac{K_s}{T_{s0}}\frac{T_{s1}}{T_{s2}}\\ \frac{K_s}{T_{s0}}\frac{T_{s1}}{T_{s2}}\frac{T_{s3}}{T_{s4}}\end{bmatrix}\Delta\omega \quad (7)$$

Mathematical model of PSS with two compensation components is shown in (7). From (1) and (7) mathematical model of the entire system can be expressed as

$$A_{GRS}=\begin{bmatrix}A & B\cdot C_s\\ B_s\cdot C & A_s\end{bmatrix}\quad B_{GRS}=\begin{bmatrix}B\\ 0\end{bmatrix}\quad C_{GRS}=\begin{bmatrix}C & 0\end{bmatrix} \quad (8)$$

Where A_{GRS}, B_{GRS} and C_{GRS} are state space matrices of a system comprised of generator, AVR and PSS. *A*, *B* and *C* are system variable matrices comprised of generator and AVR. A_s, B_s and C_s are state space matrices of PSS from (7).

To achieve optimal tuning of PSS parameters it is necessary to determine system damping as a function of parameter values. PSS structure is shown in Fig. 4.

System damping can be calculated from eigenvalues of matrix A_{GRS}.

$$\left|\lambda I - A_{GRS}\right| = 0 \quad (9)$$

State space systems in (1), (2) or (1), (3) can be written as N partial transfer functions, where N is matrix size. Characteristic equations of partial transfer functions have form: $(s-\lambda)$, of $(s-\lambda_1)(s-\lambda_2)$ for complex conjugated values of λ.

Damping coefficient of partial transfer function is

$$\xi = \frac{\sigma}{\sqrt{\sigma^2+\omega^2}} \quad (10)$$

Where $\sigma = \mathrm{Re}(\lambda)$, $\omega = \mathrm{Im}(\lambda)$.

Damping coefficient as a function of PSS parameters need to be defined:

$$\xi = f\left(K_s, T_s\right) \quad (11)$$

Time constants $T_{s\omega}$ and T_{sP} are selected for tuning since they have largest impact on the PSS phase offset and gain constants $K_{s\omega}$ and $K_{s\omega}$, as they determine main signal gain. Damping function is formed using numerical procedure for calculation of eigenvalues of system matrix. Durand-Kerner method for calculating eigenvalues is used.

$$\lambda_i(k) := \lambda_i(k-1) - \frac{\left|\lambda_i I - A_{GRS}\right|}{\prod_{k=1}^{n}\left(\lambda_i-\lambda_k\right)\Big|_{k\neq i}} \quad (12)$$

In (12), basic relation for obtaining new eigenvalues is shown. Procedure is repeated until the error threshold is reached (e.g. $\varepsilon = 10^{-6}$). Calculation of dumping function is performed for predetermined range of parameter values T_s and K_s. With the preselected time constant T_s, eigenvalues of the system matrix A_{GRS} in (8) are calculated for a range of values of K_s. In order to form the ordered set of eigenvalues, considering K_s, gain constant is incremented in small steps. For each value of K_s matrix A_{GRS} in (8) is calculated, from which eigenvalues are computed using iterative methods.

To retain the order of eigenvalues between changes of K_s, initial values $\lambda_i\left(K_s+\Delta K_s\right)$ in (12) are selected from $\lambda_i\left(K_s\right)$ of previous K_s. Although small value of ΔK_s demands large number of eigenvalue calculations, it also reduces the number of iterations in Durand-Kerner procedure (12). Damping coefficients are determined from system eigenvalues using (10). Range of values T_s and K_s is adjusted to find the area with maximum damping.

Selection of parameters for tuning is based on eigenvalues that show large sensitivity to change of parameter and have small values. After the calculation of damping functions for all partial transfer functions, only those functions are selected that are sensitive to parameter tuning and have lowest absolute value $\left|\mathrm{Re}(\lambda_i)\right|$.

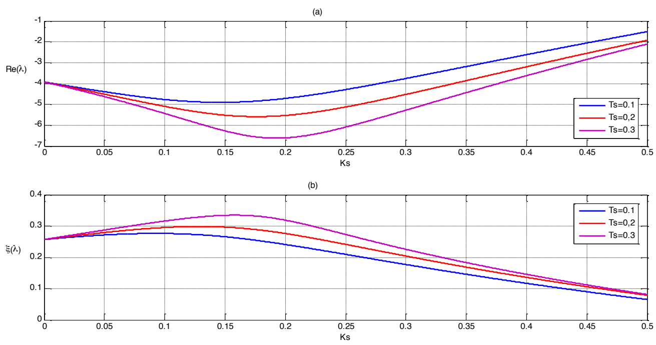

Fig. 5. Function of eigenvalues of system matrix on system parameters, for output variables, generator voltage ΔV and angular velocity $\Delta\omega$. Where figure (a) shows real part $\mathrm{Re}(\lambda)$ of the eigenvalues, and figure (b) shows damping coefficient $\xi(\lambda)$ of the system.

Optimal tuning procedure is tested on the laboratory model of synchronous generator on the power grid. System matrix A_{GRS} in (8) is determined using the identification results of mathematical model (1) and (2) with output variables $y=\left[\Delta V\,\Delta\omega\right]^T$ shown on fig. 1. Using eigenvalues calculated from (12), for applied change of stabilization gain Ks and time constant Ts, functional dependence of

$\mathrm{Re}(\lambda)$ (Fig. 5a) and functional dependence of damping coefficient $\xi(\lambda)$ (Fig. 5b) is obtained. Output variables of mathematical model are generator voltage ΔV and change of angular velocity $\Delta\omega$. From the results on Figure 5, tuning parameters are chosen based on maximum damping, $Ts = 0.03$ and $Ks = 0.15$.

The same calculation is performed for model of synchronous generator (1) and (3), for output variables $y = \left[\Delta V\, \Delta P\right]^T$. Results of identification are shown in Fig 3. Functional dependences $\mathrm{Re}(\lambda) = \mathrm{f}(\mathrm{Ks}, \mathrm{T}_{s1}, \mathrm{T}_{s3})$ and $\xi = \mathrm{f}(\mathrm{Ks}, \mathrm{T}_{s1}, \mathrm{T}_{s3})$ for selected partial transfer function are shown on Fig. 6.

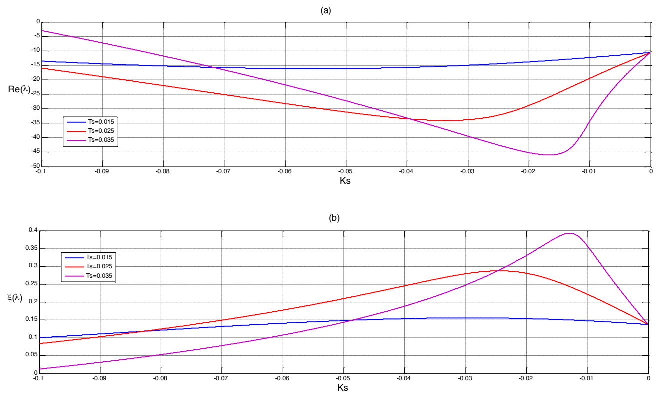

Fig. 6. Functional dependence of system matrix eigenvalues on tuning parameters, for output variables generator voltage ΔV and generator power ΔP. Where figure (a) shows real part $\mathrm{Re}(\lambda)$ of the eigenvalues, and figure (b) shows damping coefficient $\xi(\lambda)$ of the system.

Parameters for maximum damping are $Ts = 0.035$ and $Ks = -0.12$. In the examples shown, other eigenvalues had large real component or small sensitivity to PSS tuning parameters. PSS parameter tuning was applied on laboratory model of synchronous generator on the grid, with results shown in Figure 5. Step generator voltage reference signal was applied to the tuned model. Voltage change is $\Delta V_{ref} = -0.1$. Experiment results are shown in Fig. 7.

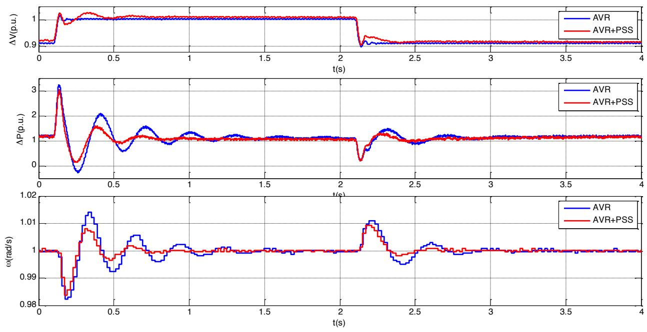

Fig. 7. Functional dependence of system matrix eigenvalues on tuning parameters, for output variables ΔV and ΔP.

In the experiment, change of angular velocity $\Delta\omega$ was used for system stabilization. For next example, results of parameter tuning were applied, shown in Fig. 6. Comparison of system responses and measurement results of laboratory model are shown in Fig. 8. Stabilization of electromechanical oscillations is performed using active power differential ΔP.

In the third experiment, both stabilization signals $\Delta\omega$ and ΔP were used, with PSS formed according to IEEE PS2B. PSS parameters for input $\Delta\omega$ are set from results in Fig. 5. ($Ts = 0.03$ and $Ks = 0.15$). Parameters for input ΔP $Ks = 0.15$ are set from results in Fig. 6. ($Ts = 0.035$ and $Ks = -0.12$).

Comparison of system responses of generator voltage ΔV, angular velocity $\Delta\omega$ and active power ΔP, for AVR and AVR+PSS is shown in Fig. 9.

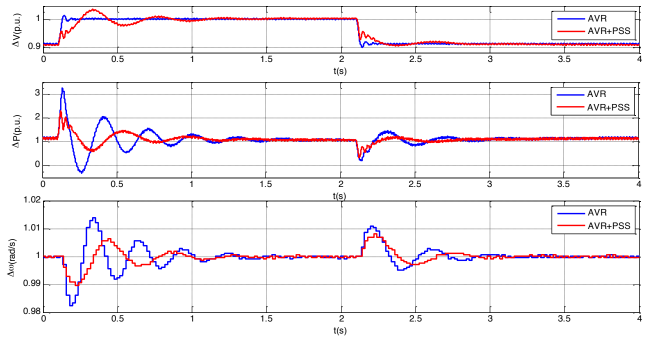

Fig. 8. Comparison of system responses of voltage ΔV, active power ΔP, angular velocity $\Delta\omega$, for step change of generator voltage reference, with and without PSS.

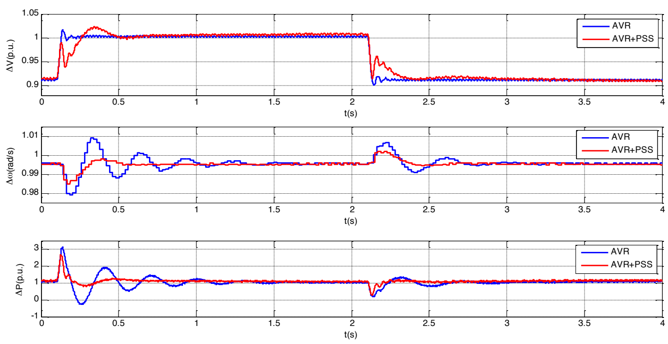

Fig. 9. Comparison of system responses of voltage ΔV, angular velocity $\Delta\omega$, active power ΔP, for step change of generator voltage reference, with and without PSS.

Results obtained from actual generator show the efficiency of the described process of PSS parameter tuning.

4. Conclusion

In the paper, the procedure of mathematical model identification of synchronous generator is presented. Kalman filter method is applied to achieve stable identification procedure with excellent matching of measurement and simulation results. Mathematical model of synchronous generator has two output values. The first in both cases being the generator voltage, and the other is used as PSS input. The procedure is more time consuming during model identification, but provide better results during PSS parameter tuning.

Described tuning procedure produces results as sensitivity to parameter change. Procedure was used for a large range of parameter values, providing a good insight in the sensitivity of procedure for individual parameter values. By using the measured values used in AVR as inputs for parameter tuning, measurement and signal processing errors are eliminated, contributing to the procedure accuracy. Testing on the actual generator shows feasibility of use of suggested procedure of PSS parameter tuning. Matlab and Simulink were used for procedure implementation. Measurements and control systems on laboratory model were implemented using XPC Toolbox from Matlab library.

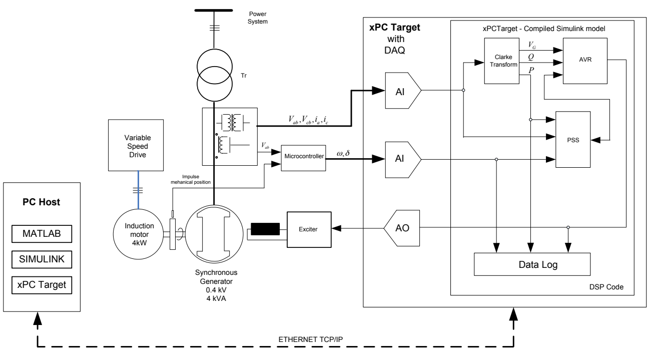

Fig. 10. The principle diagram of the laboratory model based on MATLAB xPC Target.

Fig. 10 shows principle diagram of synchronous generator laboratory model on which testing of the proposed procedure of optimal parameter setting of the power system stabilizer was connected. The laboratory model consists of synchronous generator connected to a power grid and an induction motor with speed controller as a mover of the generator. Control, measurement and processing of measured data was realised using a system of two computers – host and target. Host computer is running MATLAB and Simulink XPC Target module. Target computer is equipped with a DAQ card and is running XPC Kernel from MATLAB XPC Target software.

The corresponding model was developed in Matlab Simulink environment on host computer, and then compiled and transferred to the target computer. The described method accomplishes fast digital controller, where time discretization is $T_D = 10^{-4}$ s. The laboratory model presented in Fig. 10 is used in both cases: in the process of identifying as well as testing of the effectiveness of the proposed algorithm for determination of optimal parameters of PSS.

References

[1] J. P. Kunder, Power System Stability and Control, Palo Alto, California: Electric Power ResarchInstitute, 1994

[2] Sumina, D.& Bulic, N.& Miskovic, M., "Parameter tuning of power system stabilizer using eigenvalue sensitivity", Electr. Power Syst. Res., vol. 81, 12, 2011, p.2171-2177

[3] R. E. Kalman, "A new approach to linear filtering and prediction problems," J. Basic Eng., vol. 82, no.1, pp. 35–45, Mar. 1960

[4] B. D. O. Anderson and J. B. Moore, Optimal Filtering. New York: Dover, 2005.

[5] Feldkamp, L., Prokhorov, D., Eagen, C., Yuan, F.: "Enhanced multi-stream Kalman filter training for recurrent networks," in Nonlinear Modeling: Advanced Black-Box Techniques, J. Suykens and J. Vandewalle, Eds., Kluwer Academic Publishers, 1998, pp. 29-53

[6] Weierstraß, Karl (1891). "Sitzungsberichte der königlich preussischen Akademie der Wissenschaften zu Berlin".

[7] Durand, E. (1960). Masson et al, ed. "Solutions Numériques des Equations Algébriques, vol. 1".

[8] Mišković, Mato; Mišković, Ivan; Mirošević, Marija, „Tuning the Parameters of the Voltage Regulator by the Identified Mathematical Model of Synchronous Generator" // Procedings on 4th International Conference on Power Engineering, Energy and Electric Drives / Colak, Ilhami, editor(s). Istanbul : Gazi University, Ankara, 2013. 1-4

[9] Mišković, Mato; Mirošević, Marija; Mišković, Ivan. "On-line Identification of Synchronous Generator Mathematical Model" // ICRERA 2012 Proceedings / Kurokawa, Fujio, editor(s). Nagasaki, Japan : University of Nagasaki, 2012. 1-3