ISSN 0005-1144
ATKAFF 51(2), 127–137(2010)

Zlatka Tečec, Ivan Petrović, Jadranko Matuško

A Takagi-Sugeno Fuzzy Model of Synchronous Generator Unit for Power System Stability Application

UDK 621.313.32.072.8
IFAC 5.5.6; 5.5.4

Original scientific paper

This paper presents a Takagi-Sugeno (TS) synchronous generator unit model intended for application in an autotuning power system stabilizer. The model takes into account all three process variables that can affect synchronous machine dynamics regarding stability - beside usually used active and reactive power (P and Q) it includes also line reactance (x_m). It is shown that the proposed model gives very good results in spite of simple third order local model used as the consequent part of the proposed TS structure. This makes the model appropriate for implementation on simple microprocessor platforms. Because P, Q and x_m are included as TS model premises, it is enough to identify parameters of models in consequent part of TS model off-line. In this way possible numerical instability is avoided, which is common to adaptive PSSs that calculate controller's parameters directly from on-line identified plant parameters.

Key words: Modelling, Electrical machines, Takagi-Sugeno model, Power system stabilizer

Takagi-Sugeno model sinkronog generatora namijenjen primjenama u samopodesivim stabilizatorima elektroenergetskog sustava. U ovome je radu predstavljen Takagi-Sugeno (TS) model sinkronog generatora namijenjen primjenama u samopodesivim stabilizatorima elektroenergetskog sustava. Model uzima u obzir sve tri procesne varijable koje utječu na stanje sinkronog stroja s obzirom na njegovu stabilnost – uz uobičajeno korištene radnu i jalovu snagu (P i Q) model također uključuje i ekvivalentnu mrežnu reaktanciju (x_m). Pokazano je da predloženi model daje vrlo dobre rezultate unatoč jednostavnom modelu trećeg reda u posljedičnom dijelu TS strukture. To čini predloženi model prikladnim za primjenu na jednostavnim mikroprocesorskim platformama. Budući da su P, Q i x_m uzročne varijable TS modela, dovoljno je off-line identificirati njegov posljedični dio. Na taj su način izbjegnuti problemi numeričke nestabilnosti, karakteristični za adaptivne strukture PSS-a koji parametre regulatora proračunavaju na temelju on-line identificiranog modela procesa.

Ključne riječi: modeliranje, električni stroj, Takagi-Sugeno model, stabilizator elektroenergetskog sustava

1 INTRODUCTION

Power system stabilizers (PSSs) are used as a part of the synchronous generator automatic voltage regulators (AVRs) in order to damp out the low frequency local and system power oscillations. Today's AVRs commonly include so called conventional PSSs (CPSS), where the term conventional in this context means nonadaptive. Although modern types of CPSS like IEEE PSS2B and PSS4B [1] can be very effective in damping both local and system power oscillations, tuning of these two types of PSS can be time consuming and requires expert knowledge during commissioning. Additionally, problems with CPSS may occur when a CPSS properly tuned for one operating regime, has to operate in another very different regime.

To resolve these problems a number of methods, mainly in the field of adaptive control, has been proposed. Some of the commonly used methods are gain scheduling, indirect and direct adaptive control using artificial intelligence (mostly neural networks and fuzzy logic) [2]. The largest group of the proposed adaptive PSSs consists of indirect selftuning power system stabilizers [2],[3-8]. Those PSSs provide better dynamic performance over a wide range of operating conditions, but they suffer from the significant drawback of requiring model parameter identification, state observation and feedback gain calculations in real-time. Errors in parameter identification can significantly degrade performance and eventually cause the instability of the overall control algorithm. The additional drawback of a number of adaptive stabilizers presented in the last two decades is the fact that they require implementation in floating point arithmetic despite the facts that today's digital AVRs, within which PSSs typically have to be implemented, are mostly implemented in 16 or 32-bit fixed point processors. Thus additional hardware modifications of the existing AVRs need to be done in order to implement such algorithms. The mentioned drawbacks could be reason why, despite of numerous adaptive PSS proposed in the last two decades, vary few of them have been used in the practice. The problems related to the conventional and adaptive PSSs have motivated researchers to recently propose simpler solutions [9], [10]. Our work is also motivated by this paradigm.

In this paper we propose a relatively simple Takagi-Sugeno (TS) fuzzy model of synchronous generator unit, which is suitable for use in an easy-to-implement autotuning power system stabilizer. The motivation of using TS fuzzy model is rooted in its ability to accurately model nonlinear system behavior with a relatively small number of linear models [11, 12]. Smooth transitions between these linear models are achieved by using fuzzy rules. The proposed TS model combines active power, reactive power and line reactance signals as premise variables. Due to the fact that these three signals completely describe the state of synchronous generator units [13, 14], the proposed PSS can use off-line TS model identification process and provide satisfactory performance over the wide range of operation conditions. Similar fuzzy solutions, that can be found in literature, mainly use only signals of active and reactive power as premise variables [6, 15], and therefore they require on-line parameter estimation.

The rest of the paper is structured as follows. Section 2 describes TS fuzzy model structure, the mathematical model of synchronous generator unit and developing process of the proposed TS model of the synchronous generator unit. Section 3 shows simulation results of the proposed TS synchronous generator unit model as well as simulation results of the newly proposed autotuning PSS utilizing the proposed TS model. Conclusions are given in Section 4.

2 TAKAGI-SUGENO MODEL OF SYNCHRONOUS GENERATOR UNITS

2.1 Takagi-Sugeno Fuzzy Model Structure

A Takagi-Sugeno (TS) structure can be used both as a plant model [6], or as a regulator, [15, 16]. In Takagi-Sugeno model approach [11, 12] a plant is described by a set of simple local linear regression models, each valid for particular operating area. The plant model output is a combination of local models outputs according to fuzzy rules, which are defined with variable determining operating area (premise variables). The fuzzy rules are structured as follows:

$$R^i\text{: } \mathbf{if} \left[x_1(k) \text{ is } F_1^i\right] \& \ldots \& \left[x_{\mathrm{nx}}(k) \text{ is } F_{\mathrm{nx}}^i\right]$$
$$\mathbf{then}\, y^i(k+1) = p_0^i + p_1^i m_1(k) + p_{\mathrm{nm}}^i m_{\mathrm{nm}}(\mathrm{k}),$$
$$i = 0, 1, \cdots, \mathrm{nr}, \tag{1}$$

where:

R_i – *i*-th inference rule,

x_j – *j*-th premise variable,

F_j – fuzzy set defined on the universe of discourse of the variable x_j, used in *i*-th inference rule

y_i – output of the *i*-th input/output (I/O) local models

$$p = [a_1 a_2 \ldots a_{\mathrm{na}} b_1 b_2 \ldots b_{\mathrm{nb}} c_1 c_2 \ldots c_{\mathrm{nc}}] \tag{2}$$

– parameters of i-th I/O local model

$$\mathbf{m}^T(k) = [-y(k) \ldots - y(k-\mathrm{na}+1)\ u(k-d) \ldots$$
$$\ldots u(k-d-\mathrm{nb}+1) \quad \zeta(k-1) \ldots \zeta(k-\mathrm{nc})] \tag{3}$$

– regression vector where *u* represent input of the model, *y* output of the model and *d* is process dead time,

nr – number of fuzzy rules.

For given values of the premise variables $x_j(k)$, the final output of the fuzzy plant model $\hat{y}$ is inferred by taking the weighted average of the local model outputs y_i:

$$\hat{y}(k+1) = \frac{\sum\limits_{i=1}^{\mathrm{nr}} \mu^i\left(\mathbf{x}(k)\right) y^i(k+1)}{\sum\limits_{i=1}^{\mathrm{nr}} \mu^i\left(\mathbf{x}(k)\right)} \tag{4}$$

where:

$$\mu^i\left(\mathbf{x}(k)\right) = \bigwedge_{j=1}^{\mathrm{nx}} \mu_j^i\left[x_j(k)\right] \tag{5}$$

are membership functions of the fuzzy set F_j^i.

It means that a local model in the consequent part of each fuzzy rule describes plant dynamics for the operating area depending on the premise part. A value of premises defines a rule weigh (5), which indicate the contribution of the *i*-th rule to the model output.

In a process of defining structure of local linear models in consequent part of TS model as well as premise variables, mathematical model of the plant has to be taken into account.

2.2 Physical Mathematical Model of the Generator Unit

As a starting point for the design of the power system stabilizer based on fuzzy model, machine-infinite bus system model will be used (Fig. 1). Such a model is generally described by the 7th order nonlinear model given by the

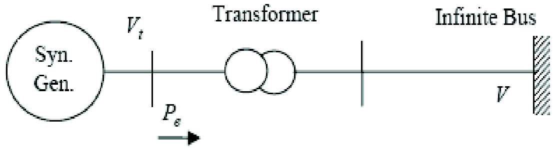

Fig. 1. Infinite bus system

following equations [17], [18]:

$$\begin{aligned}
V_d &= -r_a \cdot i_d + \frac{1}{\omega_s} \cdot \frac{d\psi_{d\Sigma}}{dt} - \omega \cdot \psi_{q\Sigma} \\
V_q &= -r_a \cdot i_q + \frac{1}{\omega_s} \cdot \frac{d\psi_{q\Sigma}}{dt} + \omega \cdot \psi_{d\Sigma} \\
e &= x_{ad} \cdot i_f + \frac{x_{ad}}{\omega_s r_f} \cdot \frac{d\psi_f}{dt} \\
0 &= r_D \cdot i_D + \frac{1}{\omega_s} \cdot \frac{d\psi_D}{dt} \\
0 &= r_Q \cdot i_Q + \frac{1}{\omega_s} \cdot \frac{d\psi_Q}{dt} \\
\frac{d\delta}{dt} &= \omega_s(\omega - 1) \\
\frac{d\omega}{dt} &= \frac{1}{T_m} \cdot (T_t - T_{el})
\end{aligned} \tag{6}$$

where *V* stands for stator voltage, *i* for stator currents, ω_s for synchronous rotor speed, *r* for inductance, *x* for reactance, Ψ for magnetic flux, ω for rotor speed, δ for load angle and *T* for torques. Subscripts are defined as follows: *d* and *q* stands for Parks *d* and *q* axes of stator winding and *D* and *Q* for Parks *d* and *q* axes of damping winding.

The transient effects in stator and the effects of rotor amortization windings can be neglected, and therefore the nonlinear model (6) can be reduced to the third order model given with the following equations:

$$\begin{aligned}
\frac{dE_{q'}}{dt} &= \frac{\omega_s r_f x_{ad}^2}{\omega x_{d\Sigma'} x_f^2} V_m \cos\delta + \omega_s e - \\
&\quad - \frac{\omega_s r_f x_{d\Sigma} x_{ad}}{x_{d\Sigma'} x_f} E_{q'} \\
\frac{d\omega}{dt} &= \frac{1}{T_m} \left[T_t - \frac{1}{\omega x_{d\Sigma'}} E_{q'} V_m \sin\delta + \right. \\
&\quad \left. + \frac{x_{d\Sigma'} - x_{q\Sigma}}{\omega^2 x_{d\Sigma'} x_{q\Sigma}} \frac{{V_m}^2}{2} \sin 2\delta - D(\omega - 1) \right] \\
\frac{d\delta}{dt} &= \omega_s(\omega - 1)
\end{aligned} \tag{7}$$

Although non-linear relationships are present in power systems, electromechanical oscillations don't have nonlinear character [19]. Therefore, the linear, small perturbation model of the machine-infinite bus system, originally developed by Heffron and Philips [20], can be used in the process of developing TS model intended for power stability applications.

Linearization of the model (7) gives well-known Heffron and Filips model [18] given by equations (8) and graphically depicted in Fig. 2.

$$\begin{aligned}
\Delta E_{q'} \frac{1 + sK_3 T_{d0'}}{K_3} &= -K_4 \Delta\delta + \Delta e + K_8 \Delta V_m \\
\Delta\omega \left(s + \tfrac{D}{T_m} \right) &= \tfrac{1}{T_m} \left[\Delta T_t - K_2 \Delta E_{q'} - \right. \\
&\quad \left. -K_1 \Delta\delta - K_9 \Delta V_m \right] \\
\Delta V_g &= K_5 \Delta\delta + K_6 \Delta E_{q'} + K_7 \Delta V_m
\end{aligned} \tag{8}$$

It can be seen that the model relates the variables of electrical torque, speed, angle, terminal voltage, field voltage and flux linkages. Constants K_1 – K_6 depend on the machine system parameters (inertias, reactances, time constants) and the operating condition (i.e. the value of active power, reactive power and line reactance).

From the block diagram shown in Figure 2, input-output model needed for TS model consequent part can be obtained. If we want to use TS model in PSS application then PSS output signal Δu_{PSS} has to be used as the model input, while any signal that contains active power oscillations can be used as the model output. In the proposed solution, the signal of integral of accelerating power ΔP_{acc} has been chosen as the model output. This signal is derived within signal processing module from frequency of the terminal voltage and a high-pass filtered integral of electrical power as in [21]. This signal, which actually represents estimated rotor speed signal ($\Delta\omega$), is used due to good establishment in conventional PSS2B type of PSS.

As can be seen from Fig. 2 synchronous generator input-output model with PI type AVR included, is of the third order. Namely, with PI type AVR included, the closed

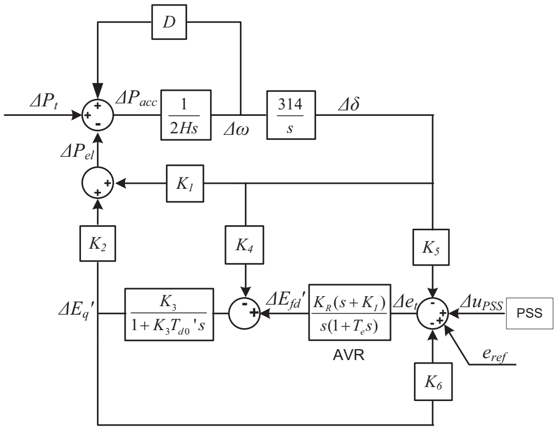

Fig. 2. Small perturbation transfer function block diagram of the machine-infinite bus system

loop from Δu_{PSS} to the signal of electrical power ΔP_{el} can be described as a second order transfer function. To obtain signal of rotor speed $\Delta\omega$, which is in the proposed structure of PSS chosen as the model output signal, signal of ΔP_{el} have to pass through the summation and the integrator. This makes transfer function from Δu_{PSS} to $\Delta\omega$ to be of the third order.

2.3 Premise Part of the TS Model of Generator Unit

As aforementioned, K_1 – K_6 depend on the machine system parameters and the operating condition. Taking into account the fact that machine system parameters don't (or slightly) vary with time, constants K_1 – K_6 depend only on the operating condition defined with three variables: active power (*P*), reactive power (*Q*) and line reactance, represented with value of equivalent reactance (x_m). These three variables are therefore used as premise variables in TS model.

Signals *P* and *Q* are available in standard AVR and can be used directly as inputs to the TS model. On the other hand equivalent reactance x_m is typically not available, and therefore it should be estimated.

The equivalent reactance x_m represents the reactances of the transmission lines between unit terminals and infinite bus. An estimation method presented in [22] is used within the TS model. In that method the equivalent reactance, seen from the unit terminals, is evaluated using the local measurements (terminal voltage *V*, *P* and *Q*). The identification procedure starts whenever dynamic oscillations in those measurements are detected. After a large disturbance, which necessarily follows change of x_m, the new reactance is estimated in relatively short time (200-500 ms). The estimation algorithm doesn't give accurate value of the reactance but chooses the closest one to it among predefined values. The algorithm can be summarized in the following steps:

1. Phase angle between terminals voltage V_g and infinite bus voltage V_m is calculated from expression

   $$\Delta\delta_e = \frac{\tau}{1+\tau s}\Delta f \approx -\frac{\omega_n^2}{2\pi}\frac{\tau}{1+\tau s}\Delta T, \qquad (9)$$

   where Δf and ΔT are deviation from nominal value of the terminal voltage frequency and period, respectively. Constant τ is the filter time constant which value has to be big enough to keep the output of within reasonable bounds.

2. If signal $\Delta\delta_e$, calculated in step 1, reaches predefined value $\Delta\delta_{emax}$ algorithm activates signal *Transient state*.

3. For *n* predefined values of x_m the value of phase angle δ_e is calculated from equation:

   $$\delta_e = \tan^{-1}\left(\frac{P}{\frac{U_g^2}{x_m} - Q}\right) = f(x_m) \qquad (10)$$

   is derived from equations for the power conditions along a line between the power plant and the load centre:

   $$P = \frac{U_g U_m}{x_m}\sin\delta_e \qquad (11)$$

   $$Q = \frac{U_g^2}{x_m} - \frac{U_g U_m}{x_m}\cos\delta_e \qquad (12)$$

4. Difference between minimum and maximum value of all $\Delta\delta_{en}$ signals and measured signal δ_e is calculated for the next $1/f_n$ seconds, where f_n represents the synchronous generator nominal frequency. The closest agreement between the phase-angle variation, calculated with an assumed x_m value, and the measured phase-angle variation δ_e determines the x_m value for generator. As the result the algorithm gives the number that defines line reactance.

The fact that the reactance x_m cannot be identified during steady state operation is only a minor handicap. A significant change of x_m is usually associated with a disturbance anyway. The accuracy of the identification depends on the number of predefined values of x_m. Normally, the selection of 2 to 4 values covering an appropriate range is mostly adequate.

To define membership functions of selected premise variables their physical characters have to be considered. Signals of active and reactive power change smoothly through the operating area of synchronous machine during normal operation. Relationship between parameters K_1 to K_6 and values of *P* and *Q* is approximately linear during those changes. On the other hand, equivalent reactance x_m changes its value discontinuously (between 2-4 different values). Additionally, relationships between parameters K_1 to K_6 and equivalent reactance x_m is generally nonlinear. Considering that, membership functions of premises are defined as follows.

Membership functions of *P* and *Q* have linear shapes with operating range divided into two or three areas (i.e. fuzzy sets). By validation and comparison of different numbers of areas we have found that two areas per variable are sufficient: P_{high}, P_{low}, and Q_{high}, Q_{low} (Fig. 3). Equivalent reactance x_m need to have discontinuous membership function. By analyzing values of reactances measured on the real power plants during the annual maintenance, we have found that also two different values are sufficient: low (0) and high (1) as shown in Fig. 3. Estimation method of x_m will therefore give one of two possible predefined x_m values. One of them will take the value of x_m measured (i.e. estimated) during commissioning, and the second one will be 0.2 p.u. greater or smaller than measured (depending on the measured value).

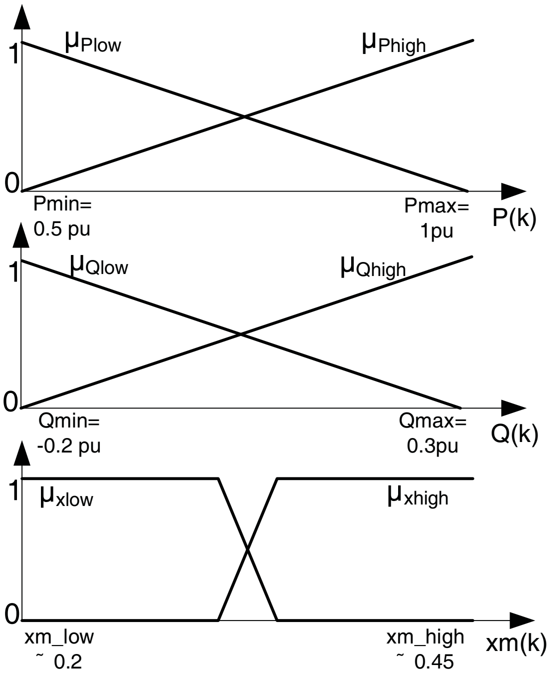

Fig. 3. Membership P, Q and x_m functions

Combination of those premise variables gives the premise part of the proposed TS model:

$$\begin{aligned}
&R^i\!: \mathbf{if}\ [P(k)\,\mathrm{is}\,P_j]\ \&\ [Q(k),\mathrm{is}\,Q_j]\ \&\ [x_\mathrm{m}(k)\,\mathrm{is}\,x_j]\\
&\qquad \mathbf{then}\, y^i(k+1) = p_0^i + p_1^i m_1(k) + p_\mathrm{nm}^i m_\mathrm{nm}(\mathrm{k}),\\
&i = 1,\cdots,8,\\
&j = low, high.
\end{aligned} \tag{13}$$

2.4 Consequent Part of the TS Model of Generator unit

As discussed in 2.2, the third order linear model can satisfactorily describe the generator unit behavior. Therefore we use the third order autoregressive models with exogenous input (ARX models) as the consequent part of the TS model. The used ARX models have the following structure:

$$\mathbf{A}(q^{-1},k)y(k+d+1) = \mathbf{B}(q^{-1},k)u(k) + c(k) \tag{14}$$

where number of parameters in A and B polynomials are: *na*=3, *nb*=1 and *nc*=0. This structure is named as ARX310. This simple structure of the local models in consequent part of the TS model makes the model computationally simple and implementable on simple processor platforms.

By inserting ARX310 models as the consequent part in (13), the final structure of the TS fuzzy model of the synchronous generator with AVR included is obtained:

$$\begin{aligned}
&R^1\!: \mathbf{if}\ [P(k)\,\mathrm{is}\,P_{low}]\ \&\ [Q(k)\,\mathrm{is}\,Q_{low}]\ \&\ [x_\mathrm{m}(k)\,\mathrm{is}\,x_{low}]\\
&\qquad \mathbf{then}\, y^1(k+1) = a_1^1 y(k) + a_2^1 y(k-1)\\
&\qquad\qquad + a_3^1 y(k-2) + b_1^1 u(k) + c^1\\
&R^2: \mathbf{if}\ [P(k)\,\mathrm{is}\,P_{low}]\ \&\ [Q(k)\,\mathrm{is}\,Q_{high}]\ \&\ [x_\mathrm{m}(k)\,\mathrm{is}\,x_{low}]\\
&\qquad \mathbf{then}\, y^2(k+1) = a_1^2 y(k) + a_2^2 y(k-1)\\
&\qquad\qquad + a_3^2 y(k-2) + b_1^2 u(k) + c^2\\
&R^3: \mathbf{if}\ [P(k)\,\mathrm{is}\,P_{high}]\ \&\ [Q(k)\,\mathrm{is}\,Q_{low}]\ \&\ [x_\mathrm{m}(k)\,\mathrm{is}\,x_{low}]\\
&\qquad \mathbf{then}\, y^3(k+1) = a_1^3 y(k) + a_2^3 y(k-1)\\
&\qquad\qquad + a_3^3 y(k-2) + b_1^3 u(k) + c^3\\
&R^4: \mathbf{if}\ [P(k)\,\mathrm{is}\,P_{high}]\ \&\ [Q(k)\,\mathrm{is}\,Q_{high}]\ \&\ [x_\mathrm{m}(k)\,\mathrm{is}\,x_{low}]\\
&\qquad \mathbf{then}\, y^4(k+1) = a_1^4 y(k) + a_2^4 y(k-1)\\
&\qquad\qquad + a_3^4 y(k-2) + b_1^4 u(k) + c^4\\
&R^5: \mathbf{if}\ [P(k)\,\mathrm{is}\,P_{low}]\ \&\ [Q(k)\,\mathrm{is}\,Q_{low}]\ \&\ [x_\mathrm{m}(k)\,\mathrm{is}\,x_{high}]\\
&\qquad \mathbf{then}\, y^5(k+1) = a_1^5 y(k) + a_2^5 y(k-1)\\
&\qquad\qquad + a_3^5 y(k-2) + b_1^5 u(k) + c^5\\
&R^6: \mathbf{if}\ [P(k)\,\mathrm{is}\,P_{low}]\ \&\ [Q(k)\,\mathrm{is}\,Q_{high}]\ \&\ [x_\mathrm{m}(k)\,\mathrm{is}\,x_{high}]\\
&\qquad \mathbf{then}\, y^6(k+1) = a_1^6 y(k) + a_2^6 y(k-1)\\
&\qquad\qquad + a_3^6 y(k-2) + b_1^6 u(k) + c^6\\
&R^7: \mathbf{if}\ [P(k)\,\mathrm{is}\,P_{high}]\ \&\ [Q(k)\,\mathrm{is}\,Q_{low}]\ \&\ [x_\mathrm{m}(k)\,\mathrm{is}\,x_{high}]\\
&\qquad \mathbf{then}\, y^7(k+1) = a_1^7 y(k) + a_2^7 y(k-1)\\
&\qquad\qquad + a_3^7 y(k-2) + b_1^7 u(k) + c^7\\
&R^8: \mathbf{if}\ [P(k)\,\mathrm{is}\,P_{high}]\ \&\ [Q(k)\,\mathrm{is}\,Q_{high}]\ \&\ [x_\mathrm{m}(k)\,\mathrm{is}\,x_{high}]\\
&\qquad \mathbf{then}\, y^8(k+1) = a_1^8 y(k) + a_2^8 y(k-1)\\
&\qquad\qquad + a_3^8 y(k-2) + b_1^8 u(k) + c^8
\end{aligned} \tag{15}$$

The final output of the TS fuzzy model is inferred by taking the weighted average of the local models outputs y^i Thus, the output signal of model (13) can be defined as [23]:

$$y(k+d+1) = \sum_{i=1}^{\mathrm{nr}} v^i(k) y^i(k+d+1) \tag{16}$$

where:

$$v^i(k) = \frac{\mu^i\left(\mathbf{x}(k)\right)}{\sum\limits_{j=1}^{\mathrm{nr}} \mu^j\left(\mathbf{x}(k)\right)}. \tag{17}$$

Considering only membership functions of *P* and *Q*, the premise structure of the proposed TS model gives a surface limited with four flat surfaces (model 1 to 4 in Figure 4) representing four linear models. Involving x_m as premise variable of the TS fuzzy model, one more set of four linear

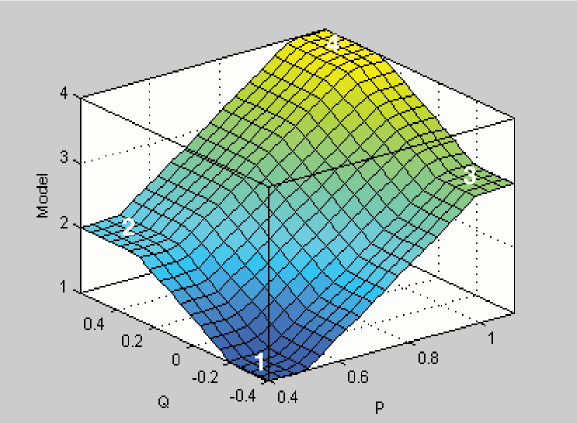

Fig. 4. P-Q premise surface

models is added. In Fig. 4 this would look like another surface placed under the existing one. If we insert linear models (15) in equation (16) the following expression is obtained:

$$y(k+d+1) = \sum_{i=1}^{\mathrm{nr}} v^i(k) \left\{ -\sum_{j=1}^{\mathrm{na}} a^i_j y(k-j+d+1) + \right. \\ \left. + \sum_{j=1}^{\mathrm{nb}} b^i_j u(k-j+1) + c^i \right\} \tag{18}$$

which can also be written as:

$$y(k+d+1) = -\sum_{j=1}^{\mathrm{na}} \left[\sum_{i=1}^{\mathrm{nr}} a^i_j v^i(k) \right] y(k-j+d+1) + \\ \sum_{j=1}^{\mathrm{nb}} \left[\sum_{i=1}^{\mathrm{nr}} b^i_j v^i(k) \right] u(k-j+1) + \sum_{i=1}^{\mathrm{nr}} c^i v^i(k). \tag{19}$$

The final expression for synchronous generator TS model can be defined from (19) as:

$$\mathbf{A}(q^{-1},k) y(k+d+1) = \mathbf{B}(q^{-1},k) u(k) + c(k) \tag{20}$$

where:

$$\begin{aligned} \mathbf{A}(q^{-1},k) &= 1 + \sum_{j=1}^{\mathrm{na}} a_j(k) q^{-j} \\ \mathbf{B}(q^{-1},k) &= \sum_{j=1}^{\mathrm{nb}} b_j(k) q^{-j+1}. \end{aligned} \tag{21}$$

Expressions for a_i and b_i are given with the following equations:

$$\begin{aligned} a_j(k) &\hat{=} \sum_{i=1}^{\mathrm{nr}} a^i_j v^i(k), \\ b_j(k) &\hat{=} \sum_{i=1}^{\mathrm{nr}} b^i_j v^i(k). \end{aligned} \tag{22}$$

Obtained model (20) is time variant linear model that can be used within classical control scheme, like pole placement. Its parameters are calculated on-line according to (22) by applying previously identified values of the TS model consequent part parameters a^i_j and b^i_j.

2.5 Identification Steps of the Consequent Part Models

Parameters a^i_1, a^i_2, a^i_3 and b^i_1 of each of the eight ARX models of the TS consequent part can be identified by using recursive least squares algorithm (RLS), [24]. Identification is performed by an embedded automatic procedure, which start identification of a local model only when the generator is in corresponding operating point defined by the TS model premise part parameters. Other two conditions that have to be fulfilled to start identification are: 1) synchronous machine has to be in steady state, and 2) identification error signal (difference between measured and estimated output model signal) have to be greater then a predefined level (i.e. 4%). Identification procedure ends successfully when synchronous machine passes through all eight operating areas defined by the TS premise part. Parameter estimation process stops whenever one of the following conditions occurs: (i) transient state is detected, i.e. large change of the line reactance x_m occurs; (ii) synchronous generator run out of operating point defined by TS model premise parts or (iii) identification error becomes less than defined. The last condition indicates the successful end of the identification procedure. Graphically the identification procedure is shown in Fig. 5.

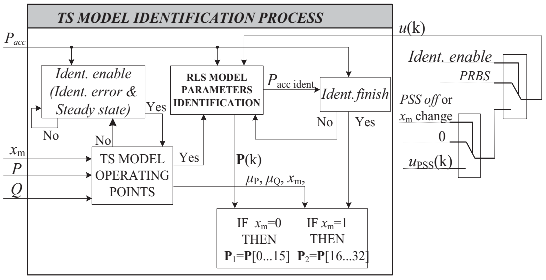

Fig. 5. Identification procedure of the TS model consequent part

Changes of the line reactance x_m are usually not possible during the PSS commissioning, and therefore only parameters of four consequent ARX models, which correspond to the actual value of the line reactance, are identified at that time. Parameters of other four consequent ARX models are identified during normal operation of the PSS, after the x_m estimation algorithm detects sufficiently large change of line reactance x_m.

3 SIMULATION RESULTS

The nonlinear model of a real power plant is implemented in *MATLAB/Simulink* simulation environment for the purpose of testing proposed TS model. It consists of a single machine equipped with control systems and connected to infinite bus [25]. *Synchronous machine* block from *MATLAB/Simulink SimPowerSystems* [26] is used to represent a synchronous generator connected to an infinite bus (*Three-phase programmable voltage source block*) through a three-phase transformer and transmission lines. The ability of changing the line reactance is modelled as well. Equations used to simulate AVR and conventional PSS (IEEE type PSS2B) are given in [27].

3.1 TS model validation

MATLAB System Identification Toolbox is used to verify structure of the TS model consequent part. Verification was done through the identification of the simulated nonlinear plant by several different linear ARX structures. During the identification experiment a Pseudo Random Binary Signal (PRBS) with T = 0.05 s, n = 11 and amplitude 0.003 p.u. around the steady-state value was used as input signal u_{PSS} to the nonlinear plant model. The signal of integral of accelerating power was recorded as the output signal. The results of the identification process are summarized in Table 1. The numbers in the end of ARX model names means number of ARX model parameters: ARX[*na*][*nb*][*nc*] where parameters *na*, *nb* and *nc* are given in (21).

Table 1. Fits in % of investigated ARX models

Model	ARX310	ARX422	ARX720	ARX210
na, nb, nd	3,1,0	4,2,2	7,2,0	2,1,0
Fit [%]	99,40	99,62	99,81	98,41

It can be seen that difference between measured output signal (real Pacc) and ARX310 structure is only 0.6%. Comparison of Bode diagrams of considered ARX structures is shown in Figure 6. From Bode diagrams it can be seen that matching between ARX310 and ARX720 (which represent best matching to nonlinear plant model) in interesting frequency domain (0.5 to 3 Hz) is satisfying.

Figure 7 shows comparisons between the output signal of the proposed TS model $P_{acc,ident}$ and signal of integral of acceleration power obtained on simulated nonlinear power plant model (P_{acc}). Changes in reactive power Q was realized by applying step changes in AVR reference voltage. Line reactance had low value (*xlow*). It can be seen that identification error in all operating condition is less then 4%. Such level of identification error is acceptable for autotuning power system stabilizer application.

3.2 Validation of the Identification Procedure

The identification procedure is presented in Fig. 8. The graph a) shows two input identification signals. Signal $u(t)$ is signal applied to AVR when identification process is active and signal *test_PRBS*(t) is applied to AVR when identification process is not active in order to estimate error level. Both signals are of PRBS type with small enough amplitude and therefore they don't induce any instabilities of the synchronous generator.

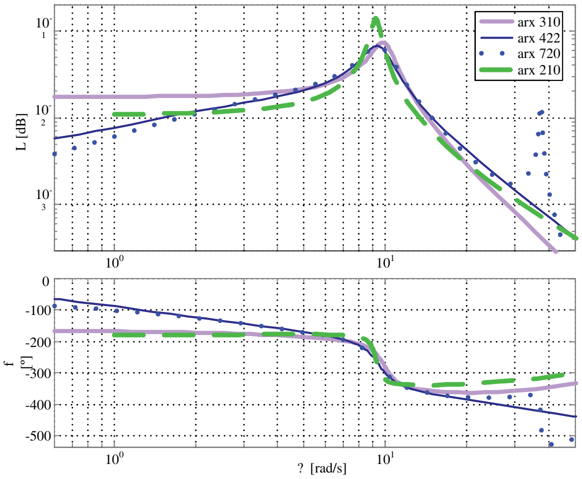

Fig. 6. Bode diagrams of investigated ARX models

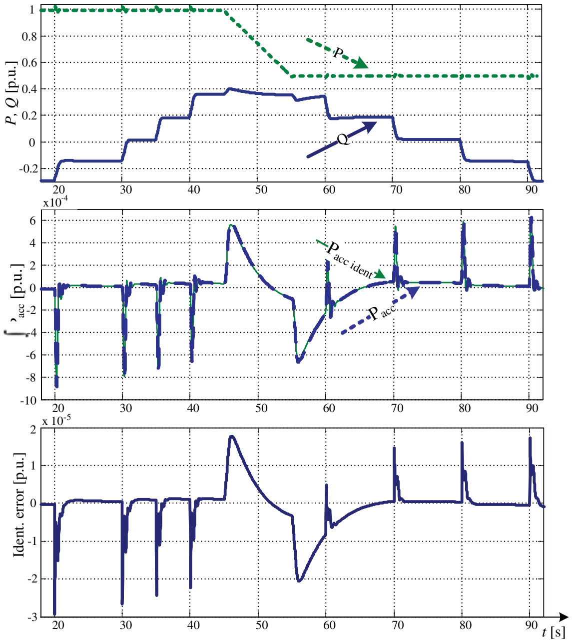

Fig. 7. TS model results, low x_m value

The graphs b) and c) show values of active and reactive power, respectively, and from them the operating point can be restored. It can be seen that synchronous generator passes through the four operating points defined by premise part of the first four rules of TS model (15). The graph d) represents measured and estimated $Pacc(t)$ signals together with $Ident\_enable(t)$ signal which represents the state of the identification procedure. High level of $Ident\_enable(t)$ signal indicates that the identification process active .

The identification procedure can be shorten if the commissioning staff make the synchronous generator to operate in operating points defined by TS model premise part. However if it is not possible to pass through all four operating points during the commissioning process, the identification procedure will automatically continue when a no visited operating point becomes active later during normal operation. When identification of all four ARX models for current line reactance value is done, the process of automatic tuning of PSS according to the pole placement control algorithm is performed and PSS is turned on.

If the line reactance estimation algorithm detects a sufficiently large line reactance change during the normal operation, the identification procedure is restarted in order to identify the remaining four TS consequent ARX models. The identification is performed during normal plant operation, when the system is in the steady-state and when it operates in operating points defined by TS premise parts. Duration of this second identification process can be shorten if an autotuning PSS structure embeds statistics of the synchronous unit the most frequent operating points. This way the operating point in TS model premise parts could be automatically changed to points in which synchronous unit operates the most frequently. Until the identification procedure of remaining four linear models is done, PSS operates with parameters optimally tuned during commissioning.

3.3 Proposed TS Model within an Autotuning PSS

When the identification of the TS model consequent part (15) is done and the parameters of the linear model (20) are obtained, an appropriate PSS can be designed. To calculate PSS parameters, the pole placement control strategy is used in this paper [28]. The structure of the proposed pole-placement autotuning PSS is shown in Fig. 9. It should be said that other control approaches can be used as well.

The pole placement autotuning PSS based on the proposed TS model is implemented in the TI TMS320F2812 fixed-point DSP [29]. Its behavior has been investigated in comparison to the PSS2B PSS controller, through voltage reference step changes. Other validation cases like resistance to reactive power modulation when the mechanical power changes and behavior when the line reactance changes can be found in [29]. To perform fair comparison the conventional PSS2B was optimally tuned for nominal operating point of synchronous generator (P = 1 p.u., Q = 0, x_m =xm_low).

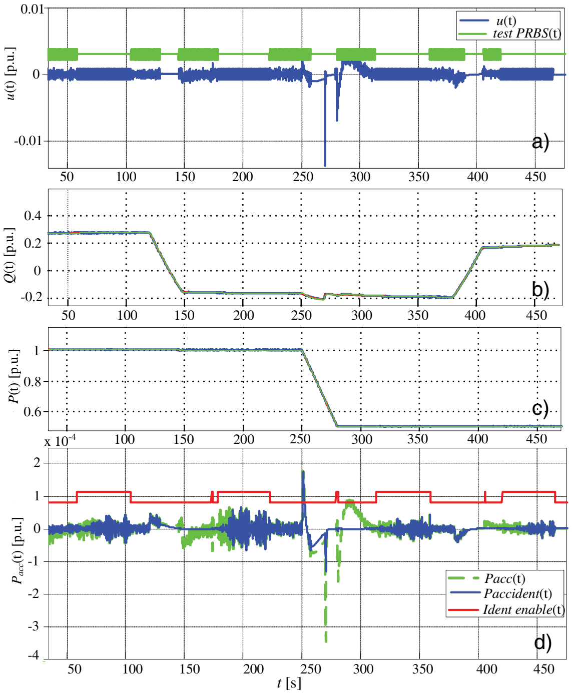

Fig. 8. Identification procedure

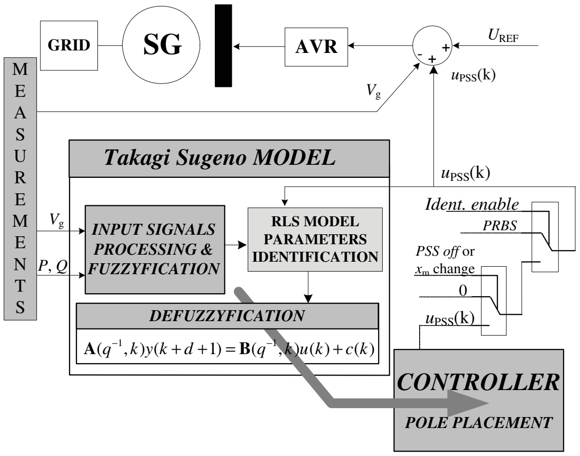

Fig. 9. The structure of the proposed autotuning PSS; SG – synchronous generator, AVR – automatic voltage regulator, U_{REF} SG voltage reference

Figures 10 and 11 show: a) signals of active power, b) signals of reactive power and c) control signals of PSSs.

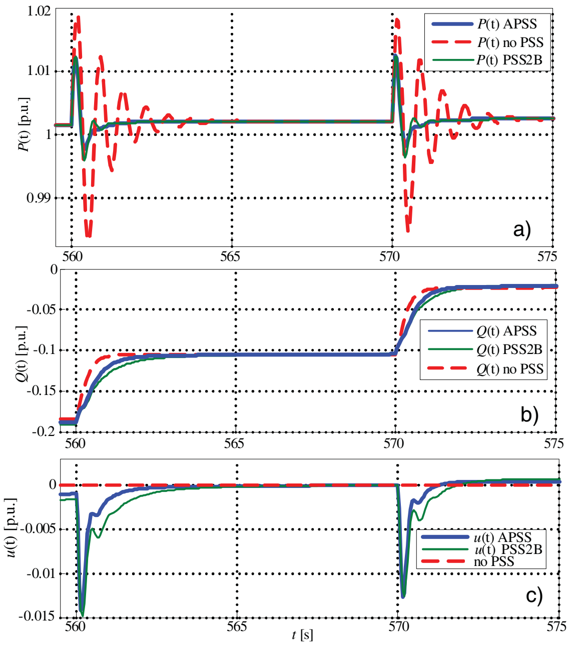

Fig. 10. System responses on step changes of the voltage reference value - nominal operating point

For the sake of comparison responses obtained by both proposed autotuning PSS and PSS2B are shown. While both PSSs provide similar responses in nominal operating point at which they were tuned (Fig. 10) and which is characterized by low value of the line reactance *xm_low*, the proposed autotuning PSS provides better responses in another operating point characterized by high value of the line reactance *xm_high*.

4 CONCLUSIONS

In the paper a new Takagi-Sugeno synchronous generator unit model intended for PSS application is proposed. The model takes into account all three variables that can affect synchronous machine behavior regarding stability: P, Q and x_m. Therefore on-line estimation of model parameters becomes unnecessary. Probably only one or two identification processes during life time will be sufficient to obtain model parameters needed for design of an autotuning PSS.

Because of using the all three variables, proposed model is particularly suitable if direct calculation of PSS parameters (i.e. self tuning schemes) and possible numerical instability common to those schemes are to be avoided. The proposed Takagi-Sugeno model can be also used in other applications involving synchronous machine control.

Simulation results show that an autotuning PSS utilizing the proposed TS model obtains very good stabilizing effects. In comparison to optimally tuned conventional PSS2B, it shows better behavior in operating points that differ from point for which is PSS2B optimally tuned.

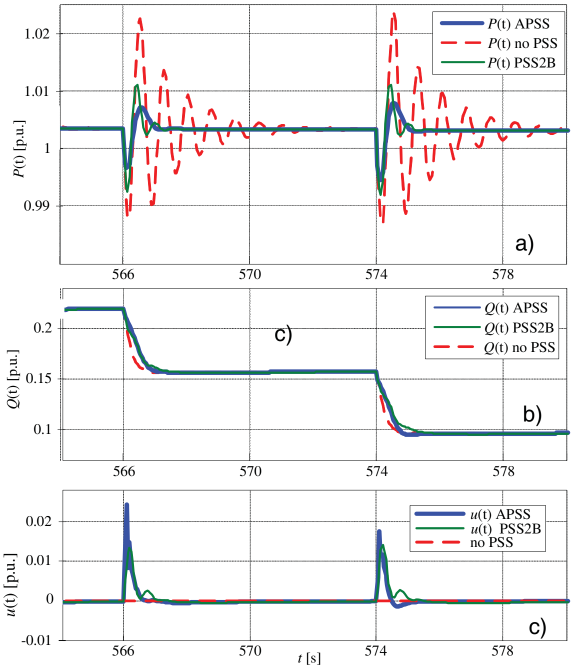

Fig. 11. System responses on step changes of the voltage reference value – out of nominal operating point

ACKNOWLEDGMENT

This research has been supported by the Ministry of Science, Education and Sports of the Republic of Croatia under grant No. 036-0363078-3018 and KONČAR Electrical Engineering Institute, Croatia.

REFERENCES

[1] I. Kamwa, R. Grondin and G. Trudel, "IEEE PSS2B Versus PSS4B: The Limits of Performance of Modern Power System Stabilizers", *IEEE Transactions on Power Systems*, vol. 20, pp. 903-915, 2005.

[2] O. P. Malik, "Artificial intelligence techniques applied to adaptive power system stabilizer design", presented at IEEE Power Engineering Society General Meeting, 2006.

[3] T. Kobayashi and A. Yokayama, "An Adaptive Neuro-Control System of Synchronous Generator for Power System Stabilization", *IEEE Transaction on Energy Conversion*, vol. 11, pp. 621-627, 1996.

[4] Ramakrishna and O. P. Malik, "Radial Basis Function Identifier and Pole-Shifting Controller for Power System Stabilizer Application", *IEEE Transactions on Energy Conversion*, vol. 19, pp. 663-670, 2004.

[5] A. Soos and O. P. Malik, "An optimal adaptive power system stabilizer", presented at IEEE Power Engineering Society Summer Meeting, 1999.

[6] T. Abdelazim and O. P. Malik, "Fuzzy Logic Based Identifier and Pole-Shifting Comtroler For PSS Application", presented at Power Engineering Society General Meeting, 2003, IEEE, 2003.

[7] D. K. Chaturvedi, O. P. Malik, and P. K. Kalra, "Generalised neuron-based adaptive power system stabiliser", *IEE Proceedings – Generation, Transmission & Distribution*, vol. 151, pp. 213-218, 2004.

[8] R. Segal, A. Sharma and M. L. Kothari, "A self-tuning power system stabilizer based on artificial neural network", *International Journal of Electrical Power & Energy Systems*, vol. 26, pp. 423, 2004.

[9] J. Ritonja, D. Dolinar, B. Grčar and D. Đonlagić, "Practical Adaptive Control for Power System Stabilizer", *Automatika*, vol. 37, 1996.

[10] S. Zhang and L. L. Fang, "Power system stabilizer based on improved simple adaptive control", presented at 3rd IEEE Conference on Industrial Electronics and Applications, Singapure, 2008.

[11] T. Takagi and M. Sugeno, "Fuzzy Identification of Systems and Its Application to modeling and Control", *IEEE Transaction on System, man and Cybernetics*, vol. 15, pp. 116-132, 1985.

[12] M. Sugeno and K. Tanaka, "Successive identification of Fuzzy Model", *Fuzzy sets and Systems*, vol. 42, pp. 315-334, 1991.

[13] M. K. El-Sherbiny and J. S. Huah, "Dynamic System Instability for Under-Excited Operation and Effect of Different Loading and Excitation Systeem", presented at IEEE Summer Meeting at Vancouver, Canada, 1973.

[14] M. Soliman, A. L. Elshafei, F. Bendary and W. Mansour, "LMI static output-feedback design of fuzzy power system stabilizer", *Expert Systems with Applications*, vol. 36, pp. 6817-6825, 2009.

[15] C. T. d. Costa, J. A. L. Barreios, R. C. L. d. Oliveira and W. Barra, "Power System Stabilizer Scheduled by a Fuzzy Logic Based Supervisor for a Local Compensator Network," presented at 2001 IEEE Porto Power Tech Conference, Porto, Portugal, 2001.

[16] M. Kashki, A. Gharaveisi and F. Kharaman, "Application of CDCARLA Techique in Designing Takagi-Sugeno Fuzzy Logic Power System Stabilizer (PSS)", presented at Power and Energy Conference PECon 2006. IEEE, Putrajaya, Malaysia, 2006.

[17] Z.Sirotić and Z.Maljković, *Sinkroni strojevi*. Zagreb: Element, 1996.

[18] P. C. Krause, *Analysis of Electric Machinery*: McGraw-Hill, 1986.

[19] F. P. DeMello and C. Concordia, "Concepts of Sinchronous Machine Stability as Affected by Excitation Control", *IEEE Transactions on Power Apparates and systems*, vol. PAS-88, 1969.

[20] W. G. Heffron and R. A. Phillips, "Effect of a Modern Amplidyne Voltage Regulator on Underexcited Operation of Large Turbine Generators", *Power Apparatus and Systems, Part III. Transactions of the American Institute of Electrical Engineers*, vol. 71, pp. 692-697, 1952.

[21] A. Murdoch and S. Venkataraman, "Integral of accelerating power type PSS part 1–theory, design, and tuning methodology", *IEEE Transactions on Energy Conversion*, vol. 14, pp. 1658-1663, 1999.

[22] P. Bonanomi and R. Bertschi, "On-line Identification of an Equivalent Reactance for Stability Applications", *IEEE Transactions on Power Apparates and Systems*, vol. PAS-100, pp. 822-826, 1981.

[23] R. Cupec, "Explicit Self-Tuning Fuzzy-Logic Controller (in Croatian)", vol. Master thesis. Zagreb: Faculty of Electrical Engineering and Computing, University of Zagreb, 1999, pp. 142.

[24] K. J. Astrom and B. Wittenmark, *Adaptive control*: Addison-Wesley Series, 1995.

[25] Z. Tecec, V. Cesic and I. Petrovic, "Some Issues of Microprocessor-based Power System Stabilizer Implementation", presented at MED '07. Mediterranean Conference on Control & Automation, Athens, Greece, 2007.

[26] "Matlab SimPowerSystems Software (Ver 4.1.1.)", Available at www.mathworks.com.

[27] "IEEE Recommended Practice for Excitation System Models for Power System Stability Studies", *IEEE Std. 421.5-2005.* , 2005.

[28] K. J. Astrom and B. Wittenmark, *Adaptive control*. USA: Addison-Wesley Publishing Company, 1995.

[29] Z. Tecec, J. Babic and I. Petrovic, "Implementation of Fuzzy-model Based Autotuning Power System Stabilizer", presented at EDPE 2009, Croatia, Dubrovnik, 2009.

Zlatka Tečec received her B.Sc.EE and PhD (in the field of power system stabilizer) degree from the Faculty of Electrical Engineering and Computing (FER) in Zagreb, in 2004 and 2010 respectively. Since 2004 she has been employed in company Končar-Electrical Engineering Institute, Zagreb, in the Department of Power electronic and control. Since then she is working in Section for Embedded Systems dealing with development, integration and testing of embedded hardware and software applied in the power engineering and rail vehicles. In the field of electric power engineering she has been working on development, implementation, maintenance and commissioning of digital voltage regulators and power system stabilizers. She published more than 20 scientific papers and practical project studies. She has been a licensed engineer of electrical engineering since 2008. As FER external associate assistant she participated in several courses.

Jadranko Matuško received his BSs, MSc and PhD degrees in electrical engineering and computing from the University of Zagreb, in 1999, 2003 and 2008, respectively. Currently he is an Assistant Professor at Department of Electrical Machines, Drives and Automation at Faculty of Electrical Engineering and Computing, Zagreb. His scientific interests include identification and estimation techniques, intelligent control in mechatronic systems.

Ivan Petrović received B.Sc. degree in 1983, M.Sc. degree in 1989 and Ph.D. degree in 1998, all in Electrical Engineering from the Faculty of Electrical Engineering and Computing (FER Zagreb), University of Zagreb, Croatia. He had been employed as an R&D engineer at the Institute of Electrical Engineering of the Končar Corporation in Zagreb from 1985 to 1994. Since 1994 he has been with FER Zagreb, where he is currently the head of the Department of Control and Computer Engineering. He teaches a number of undergraduate and graduate courses in the field of control systems and mobile robotics. His research interests include various advanced control strategies and their applications to control of complex systems and mobile robots navigation. Results of his research effort have been implemented in several industrial products. He is a member of IEEE, IFAC - TC on Robotics and FIRA - Executive committee. He is a collaborating member of the Croatian Academy of Engineering.

AUTHORS' ADDRESSES

Zlatka Tečec, Ph.D.
Končar – Electrical Engineering Institute,
Fallerovo šetalište 22, 1000 Zagreb, Croatia
email: ztecec@koncar-institut.hr
Asst. Prof. Jadranko Matuško, Ph.D.
Department of Electrical Machines, Drives and Automation,
Prof. Ivan Petrović, Ph.D.
Department of Control and Computer Engineering,
Faculty of Electrical Engineering and Computing,
University of Zagreb,
Unska 3, 10000 Zagreb, Croatia
emails: jadranko.matusko@fer.hr, ivan.petrovic@fer.hr

Received: 2010-02-22
Accepted: 2010-05-05