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Self-Tuning Power System Stabilizer Based on Recursive Least Square Identification and Linear Quadratic Regulator

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Abstract**—**Available commercial applications of power system stabilizers assure optimal damping of synchronous generator's oscillations only in a small part of operating range. Parameters of the power system stabilizer are usually tuned for the selected operating point. Extensive variations of the synchronous generator's operation result in changed dynamic characteristics. This is the reason that the power system stabilizer tuned for the nominal operating point does not satisfy preferred damping in the overall operation area. The small-signal stability and the transient stability of the synchronous generators have represented an attractive problem for testing different concepts of the modern control theory. Of all the methods, the adaptive control has proved to be the most suitable for the design of the power system stabilizers. The adaptive control has been used in order to assure the optimal damping through the entire synchronous generator's operating range. The use of the adaptive control is possible because the loading variations and consequently the variations of the synchronous generator's dynamic characteristics are, in most cases, essentially slower than the adaptation mechanism. The paper shows the development and the application of the self-tuning power system stabilizer based on recursive least square identification method and linear quadratic regulator. Identification method is used to calculate the parameters of the Heffron-Phillips model of the synchronous generator. On the basis of the calculated parameters of the synchronous generator's mathematical model, the synthesis of the linear quadratic regulator is carried-out. The identification and the synthesis are implemented on-line. In this way, the self-tuning power system stabilizer adapts to the different operating conditions. A purpose of this paper is to contribute to development of the more effective power system stabilizers, which would replace currently used linear stabilizers. The presented self-tuning power system stabilizer makes the tuning of the controller parameters easier and assures damping improvement in the complete operating range. The results of simulations and experiments show essential improvement of the synchronous generator's damping and power system stability.

Keywords**—**Adaptive control, linear quadratic regulator, power system stabilizer, recursive least square identification.

I. Introduction

THE synchronous generator (SG) is complex dynamical system. To assure safe and economical operation of the SG, a comprehensive control system with a lot of different control loops is needed. The goal of the control system is to follow the steady-state reference values and to damp the oscillations. The problem of small value oscillations of rotor speed, rotor angle and generated power is called dynamic stability problem. This is one of the main stability problems of the SG. The oscillations of the SG's quantities result in the increased losses and decreased stability limit [1].

For damping of small value oscillations, the additional damping windings on the rotor part of the SG are used. Such solution assures good damping of electromechanical oscillations. The application of the damping windings is expensive and therefore not preferable in modern SG.

Another solution for the improvement of the dynamic stability of the SG is the implementation of the additional control system for the enhanced damping. This control system, called power system stabilizer (PSS), amplifies damping of the SG's quantities [2].

The ordinary linear PSS are simply to implement but they have some weaknesses. The tuning of the controller's parameters of the ordinary linear PSS is very time exhausting. The ordinary linear PSS also enhances damping only in a part of the operating range. Mostly, the ordinary linear PSS improves dynamic stability in the area around the nominal operating point. In other part of the operating area, the ordinary linear PSS does not improve dynamic stability [3].

To enlarge the activity area of the PSS, the modern control methods must be used. The most suitable modern control theories for design and synthesis of effective PSS's are adaptive control and robust control [3]. Both control theories could be used to develop the modern PSS which will successfully damp SG's oscillations in the entire operating area.

There are many publications where adaptive and robust control approaches were used for modern PSS design. The thorough survey of these works is presented in [3]. In spite of enormous effort considering this problem, the majority of industrial SG's control systems still use the ordinary linear PSS. The reason is the complexity of the modern PSS. That is why the researchers still try to find new effective and simple solutions for this problem.

In this paper, the simple self-tuning PSS will be presented. The presented self-tuning PSS is based on the serial use of identification method, state-space observer and adjustable controller. For the identification of the SG's mathematical model, the well-known recursive extended least square identification method was used. State-space variables were estimated by means of Kalman filter. On basis of the identified mathematical model, the parameters of the Kalman filter and linear quadratic controller were calculated. The development and analysis of this control system are the main contributions of this paper.

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II. METHODS

A. Modelling of the Controlled Plant

The mathematical model of the SG linked to the network is a complex nonlinear state-space model described in many works. For the purpose of the identification and control system development and realization, this model is not convenient. For this reason, the nonlinear model was linearized and simplified [3]. The obtained simplified and linearized mathematical model of SG with voltage control system is presented with state-space equations:

$$\begin{bmatrix}\dot{\omega}_\Delta(t)\\ \dot{\delta}_\Delta(t)\\ \dot{E}_{q\Delta}(t)\\ \dot{E}_{fd\Delta}(t)\end{bmatrix}=\begin{bmatrix}-\frac{D}{2H} & -\frac{K_1}{2H} & -\frac{K_2}{2H} & 0\\ \omega_r & 0 & 0 & 0\\ 0 & -\frac{K_4}{T'_{d0}} & -\frac{1}{T'_{d0}K_3} & \frac{1}{T'_{d0}}\\ 0 & -\frac{K_5 k_{AVR}}{T_{AVR}} & -\frac{K_6 k_{AVR}}{T_{AVR}} & -\frac{1}{T_{AVR}}\end{bmatrix}\begin{bmatrix}\omega_\Delta(t)\\ \delta_\Delta(t)\\ E_{q\Delta}(t)\\ E_{fd\Delta}(t)\end{bmatrix}+\begin{bmatrix}0\\0\\0\\ \frac{k_{AVR}}{T_{AVR}}\end{bmatrix}V_{t,ref\Delta}(t) \tag{1}$$

$$\begin{bmatrix}\omega_\Delta(t)\\ \delta_\Delta(t)\\ V_{t\Delta}(t)\end{bmatrix}=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & K_5 & K_6 & 0\end{bmatrix}\begin{bmatrix}\omega_\Delta(t)\\ \delta_\Delta(t)\\ E_{q\Delta}(t)\\ E_{fd\Delta}(t)\end{bmatrix}+\begin{bmatrix}0\\0\\0\end{bmatrix}V_{t,ref\Delta}(t) \tag{2}$$

where T_m is the mechanical torque [pu], T_e is the electrical torque [pu], ω is the rotor speed [pu], δ is the rotor angle [rad], E'_q is the voltage behind transient reactance [pu], E_{fd} is the field excitation voltage [pu], V_t is the terminal voltage [pu], H is the inertia constant [s], D is the damping coefficient of the damper windings [pu/pu], ω_r is the nominal synchronous speed [rad s^{-1}], T'_{d0} is the direct axis transient open circuit time constant [s], K_1 ... K_6 are the linearization parameters [pu/pu], k_{AVR} is the exciter and the voltage controller gain [pu/pu], T_{AVR} is the exciter time constant [s] and $V_{t,ref\Delta}$ is the reference terminal voltage [pu]. With $_\Delta$ the difference from the equilibrium state is described and s denotes a Laplace variable.

B. Identification of the Controlled Plant

To determine the parameters of the mathematical model's system matrix, input matrix and output matrix, the recursive extended least square identification method (RELS) was used [4]. By means of RELS identification method the input-output description of the controlled plant was identified. The selected input signal for the identification of the discrete transfer function was reference terminal voltage ($V_{t,ref\Delta}$) and the preferred output signal for the identification of the discrete transfer function was rotor speed ω_Δ. To carry out the accurate identification by noised measured signals the added pseudo random binary input signal was used. By means of RELS identification method the discrete transfer function between $V_{t,ref\Delta}(s)$ and $\omega(s)$ was identified. For the controller development, the obtained discrete input-output model must be converted in the appropriate state-space model as described in [5].

C. Estimation of the Controlled Plant Variables

During SG's operation, the measurement of the state-space variables $\omega_\Delta(t)$, $\delta_\Delta(t)$, $E_{q\Delta}(t)$ and $E_{fd\Delta}(t)$ of the SG's mathematical model (1), (2) is difficult. To estimate the state-space variables from the input and output of the controlled plant the Kalman filter could be used.

The linear system with random disturbances and reduced number of measured state-space variables can be described by

$$\dot{\mathbf{x}}(t)=\mathbf{A}\mathbf{x}(t)+\mathbf{B}\mathbf{u}(t)+\mathbf{G}\mathbf{v}(t) \tag{3}$$

$$\mathbf{y}(t)=\mathbf{C}\mathbf{x}(t)+\mathbf{w}(t) \tag{4}$$

where $\mathbf{x}(t)$ is the vector of the state-space variables, $\mathbf{u}(t)$ is the vector of the system input variables, $\mathbf{y}(t)$ is the vector of the system output variables, $\mathbf{v}(t)$ is the system disturbance and $\mathbf{w}(t)$ is the measurement noise. $\mathbf{A}$ is the system matrix, $\mathbf{B}$ is the input matrix and $\mathbf{C}$ is the output matrix. The system is controllable and observable and the parameters of the system matrices are constant. Variables $\mathbf{v}(t)$ and $\mathbf{w}(t)$ are a white noise random variables with zero means and with covariance equal zero:

$$\mathrm{E}\{\mathbf{v}(t)\}=\bar{\mathbf{v}}=0,\quad \mathrm{cov}\{\mathbf{v}(t),\mathbf{v}(\tau)\}=\mathbf{V}\delta(t-\tau) \tag{5}$$

$$\mathrm{E}\{\mathbf{w}(t)\}=\bar{\mathbf{w}}=0,\quad \mathrm{cov}\{\mathbf{w}(t),\mathbf{w}(\tau)\}=\mathbf{W}\delta(t-\tau) \tag{6}$$

$$\mathrm{cov}\{\mathbf{v}(t),\mathbf{w}(t)\}=0 \tag{7}$$

$\mathbf{V}$ is a non-negative definite covariance matrix and $\mathbf{W}$ is a positive definite covariance matrix.

The target of the observation operation is to estimate the mathematical state-space variables of a linear system (3), (4) with the presumption that the measurement variables are deteriorated. By the estimation the quadratic cost function (8) must be minimized,

$$J=\mathrm{E}\left\{\left\|\mathbf{x}(t)-\hat{\mathbf{x}}(t)\right\|^2\right\}=\mathrm{tr}\ \mathrm{E}\left\{\tilde{\mathbf{x}}(t)\tilde{\mathbf{x}}^{\mathrm{T}}(t)\right\} \tag{8}$$

where $\hat{\mathbf{x}}(t)$ is the estimate vector of the state-space vector $\mathbf{x}(t)$ of the linear system described with (3) and (4). The estimation error $\tilde{\mathbf{x}}(t)$ is calculated by:

$$\tilde{\mathbf{x}}(t)=\mathbf{x}(t)-\hat{\mathbf{x}}(t) \tag{9}$$

The optimal estimate $\hat{\mathbf{x}}(t)$ for the discussed linear system is defined by (10):

$$\dot{\hat{\mathbf{x}}}(t) = \mathbf{A}\hat{\mathbf{x}}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{L}(t)\left[\mathbf{y}(t) - \mathbf{C}\hat{\mathbf{x}}(t)\right] \tag{10}$$

where **L**(t) is the time varying gain

$$\mathbf{L}(t) = \mathbf{P}(t)\mathbf{C}^{\mathrm{T}}\mathbf{W}^{-1} \tag{11}$$

and $\mathbf{P}(t)$ is the estimated error's covariance. For the calculation of $\mathbf{P}(t)$ the Riccati differential equation (12) must be solved [6]:

$$\dot{\mathbf{P}}(t) = \mathbf{A}\mathbf{P}(t) + \mathbf{P}(t)\mathbf{A}^{\mathrm{T}} + \mathbf{G}\mathbf{V}\mathbf{G}^{\mathrm{T}} - \mathbf{P}(t)\mathbf{C}^{\mathrm{T}}\mathbf{W}^{-1}\mathbf{C}\mathbf{P}(t) \tag{12}$$

In steady-state, the differential equation could be replaced with algebraic Riccati equation [6]:

$$\mathbf{0} = \mathbf{A}\mathbf{P} + \mathbf{P}\mathbf{A}^{\mathrm{T}} + \mathbf{G}\mathbf{V}\mathbf{G}^{\mathrm{T}} - \mathbf{P}\mathbf{C}^{\mathrm{T}}\mathbf{W}^{-1}\mathbf{C}\mathbf{P} \tag{13}$$

D. Control Algorithm

The proposed self-tuning PSS is based on the linear quadratic (LQ) controller. The state-space variable's vector of the mathematical model of the controlled plant represents the input of the LQ controller. The output of the LQ controller will be added to the reference terminal voltage ($V_{\mathrm{t,ref}\Delta}$).

The LQ regulator is based on the state-space description of the linear dynamic system described with (3) and (4). The objective of the control law is to control the state-space vector $\mathbf{x}(t)$ from any initial value to the zero state vector in such a way that infinite-horizon quadratic cost function J defined with (16) will be minimized [7].

$$J = \int_0^\infty \left(\mathbf{x}^{\mathrm{T}}(t)\mathbf{Q}\mathbf{x}(t) + \mathbf{u}^{\mathrm{T}}(t)\mathbf{R}\mathbf{u}(t)\right)\mathrm{d}t \tag{14}$$

Q is the symmetric positive semi-definite matrix and **R** is the symmetric positive definite matrix.

A feedback control law that minimizes cost function J is defined as:

$$\mathbf{u}(t) = -\mathbf{K}\mathbf{x}(t) \tag{15}$$

where **K** is the feedback gain given by:

$$\mathbf{K} = \mathbf{R}^{-1}\mathbf{B}^{\mathrm{T}}\mathbf{P} \tag{16}$$

and **P** is found by solving the algebraic Riccati equation:

$$\mathbf{A}^{\mathrm{T}}\mathbf{P} + \mathbf{P}\mathbf{A} - \mathbf{P}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^{\mathrm{T}}\mathbf{P} + \mathbf{Q} = \mathbf{0} \tag{17}$$

III. Results

The capability of the proposed self-tuning PSS was appraised by means of numerical simulations. Examined was turbo-type SG with transistor's excitation system and voltage control loop. A typical 160 MVA SG which is frequently used in references was analyzed [8].

Data of the studied linearized state-space mathematical model (1), (2) of the SG are shown in Table I where S_{n}, U_{n}, cos φ_{n} are nominal power [MVA], voltage [kV] and power factor respectively.

TABLE I
SG's Data

S_{n}=160 MVA	U_{n}=15 kV	cos φ_{n}=0.85
K_1=1.4478	K_2=1.3174	K_3=0.3072
K_4=1.8052	K_5=0.0294	K_6=0.5257
T'_{d0} =5.9 s	D=2 [pu/pu]	H=3.96 s
k_{AVR}=59 pu/pu	T_{AVR}=0.05 s	

The behavior of the non-stabilized SG in small vicinity of nominal operating point is presented in Fig. 1. The input of the SG's excitation control system ($V_{\mathrm{t,ref}\Delta}$) was combined with white noise random signal. White noise random signal was band limited, power spectral density (PSD) of the random signal amounted 0.001. In Fig. 1 the main electromechanical quantities of the SG are displayed: SG's rotor speed, SG's rotor angle and SG's stator (terminal) voltage. From the responses displayed in Fig. 1, it is obvious that the dynamics of the non-stabilized SG is weakly damped. The oscillations in all quantities are significant small-signal stability oscillations in frequency range from 0.5 Hz to 2.5 Hz [1]. These oscillations reduce quality of the SG's operation and lifetime of the SG and equipment.

To improve the oscillation's damping a self-tuning PSS was built in the SG's voltage control system. Numerical simulations were carried out for the proposed self-tuning controllers in the entire operating range. Obtained results showed the exceedingly increasing of the oscillation's damping.

To assess the impact of the state-space estimation on the damping augmentation the simulation results with and without Kalman observer are displayed. Fig. 2 displays the SG's rotor speed, SG's rotor angle and SG's stator voltage in vicinity of nominal operating point in case when self-tuning PSS with RELS identification and LQ controller was used. In this case the SG's state-space variables $\mathbf{x}(t) = \left[\omega_\Delta(t) \quad \delta_\Delta(t) \quad E_{\mathrm{q}\Delta}(t) \quad E_{\mathrm{fd}\Delta}(t)\right]$ were measured by the equipment and Kalman filter was not used. The output of the LQ controller was calculated on the basis of these measured variables.

In case when the measurement of the SG's state-space variables is not feasible the usage of the adequate state-space observer is required.

Fig. 3 displays the same SG's electromechanical quantities under same circumstances as in Fig. 2 but with a difference that instead of proper state-space measurements the Kalman filter was used. The results show that Kalman filter represents reasonable substitute to the complicated measurement system. The results obtained with Kalman filter do not deviate from the results obtained with measurements.

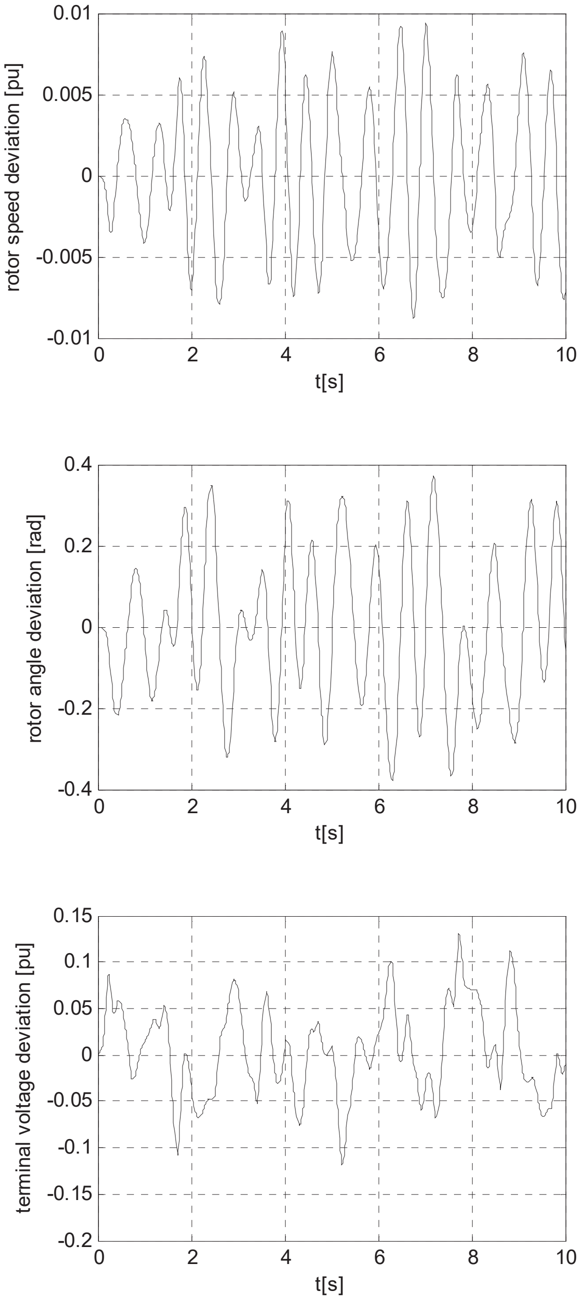

Fig. 1 Oscillations in electromechanical quantities of the non-stabilized turbo type SG

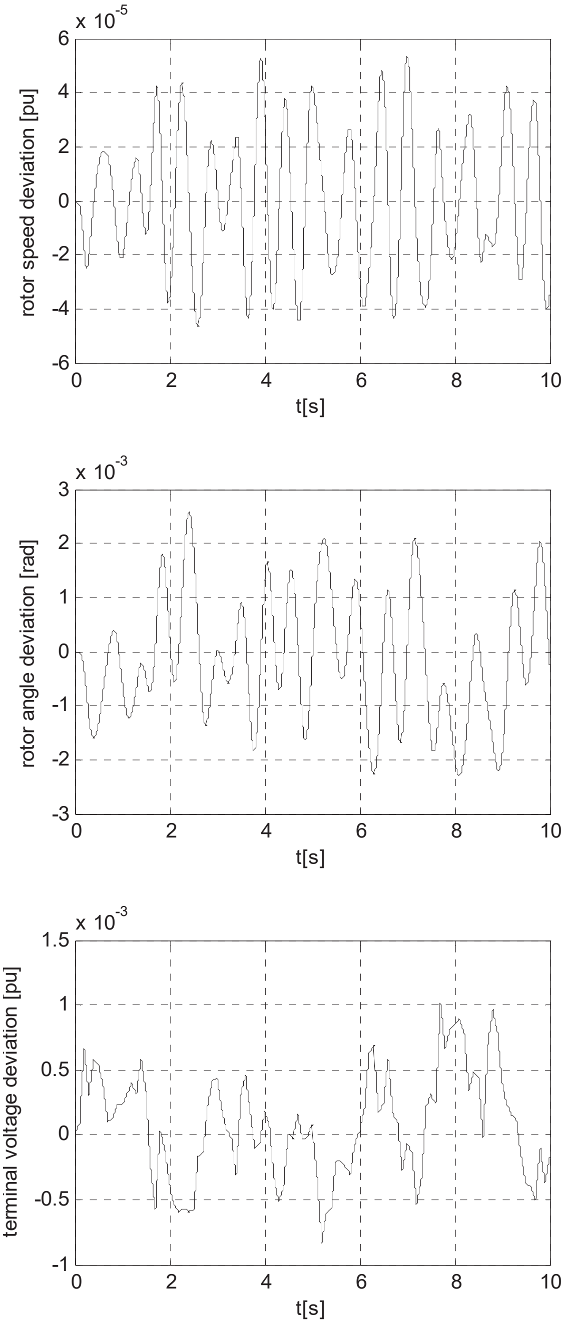

Fig. 2 Oscillations in electromechanical quantities of the turbo type SG stabilized with self-tuning PSS without Kalman observer

IV. Discussion

In the paper, the self-tuning PSS for the improvement of the dynamic stability of the SG connected to the network is proposed. The presented solution is much more complicated than ordinary linear PSS. The main benefits of the proposed stabilizer are augmented damping in the entire operating area and automated tuning procedure.

Obtained results show the advantages of the self-tuning PSS. The tuning procedure is automated and stabilizer assures increased dynamic stability in the entire operating area. The RELS identification method converges fast to the proper values of the mathematical model's parameters. The Kalman filter estimates the mathematical model's state space variables accurately and represents effective replacement for the conventional measurements.

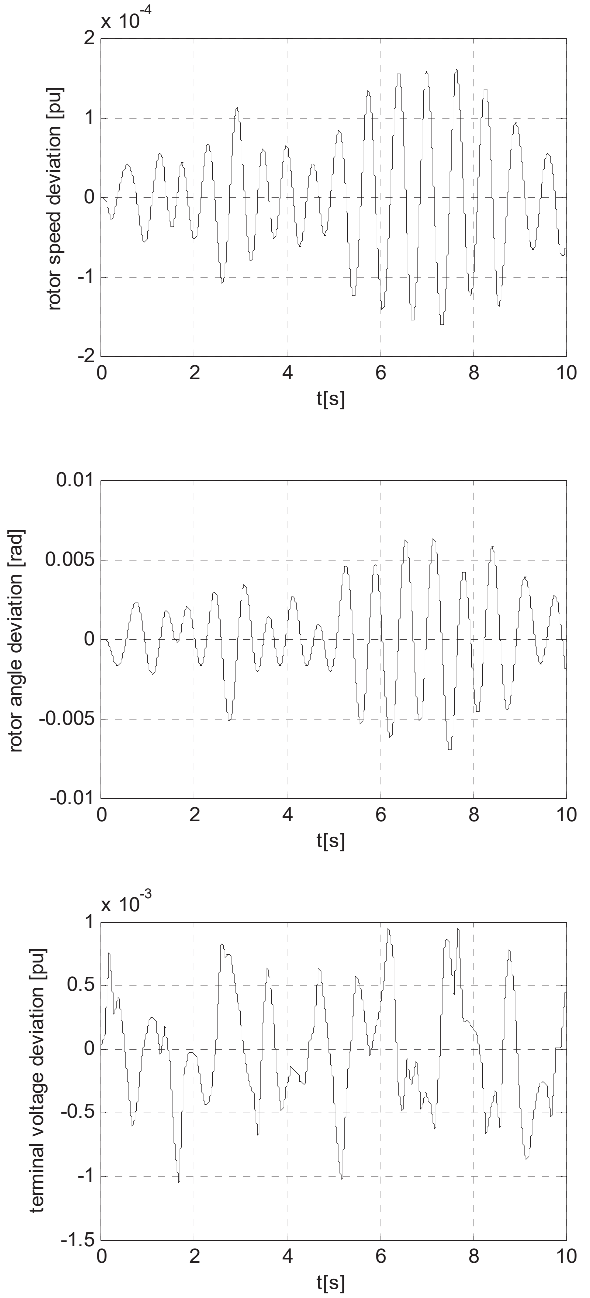

Fig. 3 Oscillations in electromechanical quantities of the turbo type SG stabilized with self-tuning PSS with Kalman observer

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