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Model Reference Adaptive Approach for Power System Stabilizer for Damping of Power Oscillations

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Abstract**—**In recent years, electricity trade between neighboring countries has become increasingly intense. Increasing power transmission over long distances has resulted in an increase in the oscillations of the transmitted power. The damping of the oscillations can be carried out with the reconfiguration of the network or the replacement of generators, but such solution is not economically reasonable. The only cost-effective solution to improve the damping of power oscillations is to use power system stabilizers. Power system stabilizer represents a part of synchronous generator control system. It utilizes semiconductor's excitation system connected to the rotor field excitation winding to increase the damping of the power system. The majority of the synchronous generators are equipped with the conventional power system stabilizers with fixed parameters. The control structure of the conventional power system stabilizers and the tuning procedure are based on the linear control theory. Conventional power system stabilizers are simple to realize, but they show non-sufficient damping improvement in the entire operating conditions. This is the reason that advanced control theories are used for development of better power system stabilizers. In this paper, the adaptive control theory for power system stabilizers design and synthesis is studied. The presented work is focused on the use of model reference adaptive control approach. Control signal, which assures that the controlled plant output will follow the reference model output, is generated by the adaptive algorithm. Adaptive gains are obtained as a combination of the "proportional" term and with the σ-term extended "integral" term. The σ-term is introduced to avoid divergence of the integral gains. The necessary condition for asymptotic tracking is derived by means of hyperstability theory. The benefits of the proposed model reference adaptive power system stabilizer were evaluated as objectively as possible by means of a theoretical analysis, numerical simulations and laboratory realizations. Damping of the synchronous generator oscillations in the entire operating range was investigated. Obtained results show the improved damping in the entire operating area and the increase of the power system stability. The results of the presented work will help by the development of the model reference power system stabilizer which should be able to replace the conventional stabilizers in power systems.

Keywords**—**Power system, stability, oscillations, power system stabilizer, model reference adaptive control.

I. INTRODUCTION

SYNCHRONOUS generators are the most important producers of the electrical energy. Changes in construction of novel synchronous generators and tightened operating conditions of contemporary power systems cause stability problems. These problems require development of more capable advanced power system stabilizers. Namely, conventional linear power system stabilizers do not fulfil the damping requirements [1].

The power system stabilizer is the part of the synchronous generator's excitation system. The excitation system generates voltage for the synchronous generator's rotor winding. The excitation system also includes control system for voltage control and reactive power control and executes protection tasks [2].

The power system stabilizers with constant parameters are still most frequently used stabilizers. For their design and synthesis, a control theory for linear systems is applicable [3]. The conventional power system stabilizers are simple to realize, but their implementation is not satisfactory. The conventional power system stabilizers do not assure satisfactory damping of the oscillations in all operating conditions. When the operation conditions of the synchronous generator are changing, these will decrease the conventional power system stabilizer performances [4]. The use of advanced control techniques can improve the damping capability of the power system stabilizers [5]. The stability problem of power system and synchronous generators is very interesting problem for analysis of new algorithms of the advanced control theories. Various applications of such concepts are found in journal articles over the recent two decades. The most convenient control strategies for power system stabilizer design are adaptive control [6] and robust control [7]. Therefore, in this paper the implementation of the adaptive control theory for improvement of the synchronous generator stability in different operating conditions is studied and presented in detail [8].

The majority of the adaptive control techniques could be divided in two groups:

- Self-tuning control systems, where the calculation of parameters of the adequate discrete controller is based on the identified parameters of the synchronous generator's mathematical model obtained by one of the parametric identification methods. A main weakness of the self-tuning control systems is not proved asymptotic stability of the entire control system. In references we can find the proof for the stability of the self-tuning control system but only in case of non-complicated tuning algorithms [9].
- Model reference adaptive control systems where the control system design and synthesis are derived from the stability theory for the entire adaptive system [10].

The model reference adaptive control methods have many advantages over the rest of the adaptive methods. The focus of this paper is dedicated to the presentation of the implementation and validation of the model reference adaptive

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control theory for the needs of the stabilization of the synchronous generator.

The paper is divided into 6 chapters: the modelling of the synchronous generator is described in Chapter II, the model reference adaptive control theory in Chapter III, the power system stabilizer, which was developed on the basis of model reference control theory is described in Chapter IV and some results are presented in Chapter V.

II. MODELLING OF THE SYNCHRONOUS GENERATOR

Mathematical model of the synchronous generator connected with transmission line to the power network can be presented with linearized model, which satisfactorily describes the behaviour of a machine in the vicinity of the operating point [1], [3].

The studied controlled plant (i.e. synchronous generator connected with transmission line to the power grid with constant voltage and frequency) is a non-linear system originally described with seven non-linear differential equations. The non-linear model is not transparent and too complicated for controlled plant analysis and for controller design and synthesis, therefore a simplified linear model of third order (Heffron-Phillips model) is mostly used [11].

The block diagram of the simplified linearized model of the synchronous generator with voltage control system with excitation system is shown in Fig. 1, 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' represents the voltage behind transient reactance [pu], E_{fd} is the field excitation voltage [pu], V_t represents the terminal voltage [pu], $V_{t,ref}$ is the reference terminal voltage [pu], H is the inertia constant of the synchronous generator with turbine [s], D is the lumped damping coefficient of all damping's windings [pu], ω_r is the synchronous speed [rad s^{-1}], T_{do}' is the time constant of the direct axis transient open circuit [s], K_1 ... K_6 are the calculated linearization parameters, k_{AVR} is the exciter and the voltage controller gain, T_{AVR} is the exciter time constant [s], s is the Laplace variable and the subscript $_\Delta$ denotes the small signal incremental quantities.

III. MODEL REFERENCE ADAPTIVE CONTROL THEORY

The theory of the model reference adaptive control systems is used for controller design and synthesis. The applied direct adaptive control procedure represents a simplified version of the model reference adaptive control based on command generator tracker theory [12].

The command generator tracker theory is considered for the controlled plant, which is described by

$$\dot{\boldsymbol{x}}_p(t) = \boldsymbol{A}_p\boldsymbol{x}_p(t) + \boldsymbol{B}_p\boldsymbol{u}_p(t) \tag{1}$$

$$\boldsymbol{y}_p(t) = \boldsymbol{C}_p\boldsymbol{x}_p(t) \tag{2}$$

where $\mathbf{x}_p(t)$ is the controlled plant's state vector, $\mathbf{u}_p(t)$ is the controlled plants' control vector, $\mathbf{y}_p(t)$ is the controlled plant's output vector, and $\mathbf{A}_p$, $\mathbf{B}_p$ and $\mathbf{C}_p$ are matrices of appropriate dimensions.

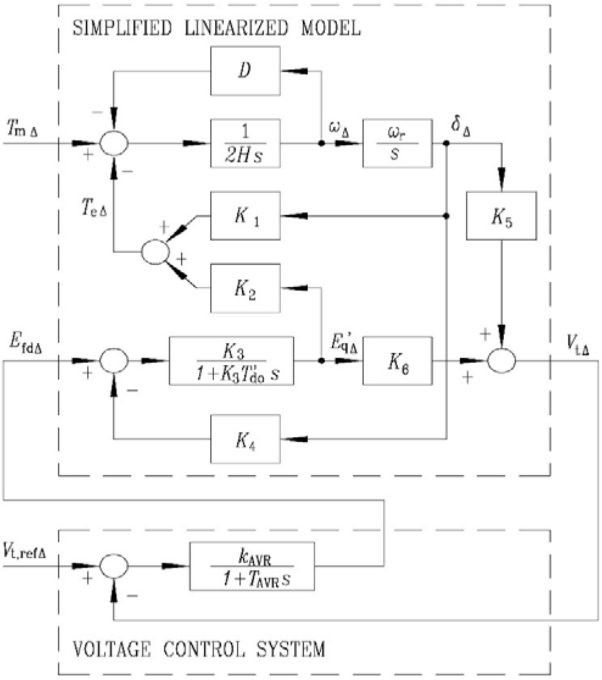

Fig. 1 Block diagram of the linearized model of the synchronous generator with the excitation system and the voltage control system

The reference model is described by

$$\dot{\boldsymbol{x}}_m(t) = \boldsymbol{A}_m\boldsymbol{x}_m(t) + \boldsymbol{B}_m\boldsymbol{u}_m(t) \tag{3}$$

$$\boldsymbol{y}_m(t) = \boldsymbol{C}_m\boldsymbol{x}_m(t) \tag{4}$$

where $\mathbf{x}_m(t)$ is the reference model's state vector, $\mathbf{u}_m(t)$ is the reference model's command vector, $\mathbf{y}_m(t)$ is the reference model's output vector, and $\mathbf{A}_m$, $\mathbf{B}_m$ and $\mathbf{C}_m$ are matrices of appropriate dimensions. The model is supposed to be stable. The dimension of the reference model's state may be less than the dimension of the plant state.

The output tracking error is defined as

$$\boldsymbol{e}_y(t) = \boldsymbol{y}_m(t) - \boldsymbol{y}_p(t) \tag{5}$$

The adaptive control algorithm which generates the control $\mathbf{u}_p(t)$ on such way that the plant output vector $\mathbf{y}_p(t)$ follows the output of the reference model $\mathbf{y}_m(t)$ without explicit knowledge of $\mathbf{A}_p$, $\mathbf{B}_p$ and $\mathbf{C}_p$ is presented with (6), (7):

$$\boldsymbol{u}_p(t) = \boldsymbol{K}_e(t)\boldsymbol{e}_y(t) + \boldsymbol{K}_x(t)\boldsymbol{x}_m(t) + \boldsymbol{K}_u(t)\boldsymbol{u}_m(t) \tag{6}$$

$$\boldsymbol{u}_p(t) = \boldsymbol{K}(t)\boldsymbol{r}(t) \tag{7}$$

where

$$\boldsymbol{K}(t) = [\boldsymbol{K}_e(t), \boldsymbol{K}_x(t), \boldsymbol{K}_u(t)] \tag{8}$$

$$\boldsymbol{r}^T(t) = [\boldsymbol{e}_y^T(t), \boldsymbol{x}_m^T(t), \boldsymbol{u}_m^T(t)] \tag{9}$$

The adaptive gains **K**(t) are obtained as a combination of the "proportional" and "integral" terms

$$\boldsymbol{K}(t) = \boldsymbol{K}_P(t) + \boldsymbol{K}_I(t) \tag{10}$$

$$\boldsymbol{K}_P(t) = \boldsymbol{e}_y(t)\boldsymbol{r}^T(t)\boldsymbol{T} \tag{11}$$

$$\dot{\boldsymbol{K}}_I(t) = \boldsymbol{e}_y(t)\boldsymbol{r}^T(t)\overline{\boldsymbol{T}} - \sigma\boldsymbol{K}_I(t) \tag{12}$$

where σ-term prevents divergence of the integral gains in the presence of disturbance, **T** and $\overline{\mathbf{T}}$ are positive definite and positive semi-definite matrices of the adaptation mechanism, respectively.

If the controlled plant is almost strictly positive real (ASPR) the asymptotic tracking will be assured. If the controlled plant is not ASPR, the additional dynamic system must be used to satisfy this condition. In this case the controlled plant should be completed with feedforward compensator such that the augmented plant is ASPR.

For the non-ASPR controlled plant presented by the following transfer function

$$\boldsymbol{G}_p(s) = \boldsymbol{C}_p(s\boldsymbol{I} - \boldsymbol{A}_p)^{-1}\boldsymbol{B}_p \tag{13}$$

The feedforward compensator is defined by the strictly proper transfer function matrix $\mathbf{R}_p(s)$ with the realization:

$$\dot{\boldsymbol{s}}_p(t) = \boldsymbol{A}_s\boldsymbol{s}_p(t) + \boldsymbol{B}_s\boldsymbol{u}_p(t) \tag{14}$$

$$\boldsymbol{r}_p(t) = \boldsymbol{D}_s\boldsymbol{s}_p(t) \tag{15}$$

In this case the augmented output $\mathbf{z}_p(t)$ is used instead of the plant output $\mathbf{y}_p(t)$:

$$\boldsymbol{z}_p(t) = \boldsymbol{y}_p(t) + \boldsymbol{r}_p(t) \tag{16}$$

The augmented system is defined as

$$\boldsymbol{G}_a(s) = \boldsymbol{G}_p(s) + \boldsymbol{R}_p(s) \tag{17}$$

Feedforward compensator $\mathbf{R}_p(s)$ must be selected such that the resulting relative degree of augmented plant $\mathbf{G}_a(s)$ is one. For example, if SISO plant $G_p(s)$ is stabilisable by a PD controller, one can use its inverse in a manner that is just a simple first-order low-pass filter.

IV. POWER SYSTEM STABILIZER

The synchronous generator connected to the electricity grid with constant voltage and frequency, completed with the excitation system with the model reference adaptive power system stabilizer and stator voltage control loop is shown in Fig. 2.

The proposed structure of the control system shows simplicity compared to other adaptive systems [9], [10]. The disturbances that affect the synchronous generator's oscillations are reference terminal voltage $V_{t,ref}$ and the mechanical torque (T_m). The changing of the synchronous generator's operation conditions represents the parameters' perturbations. The washout block in Fig. 2 is realized with a high-pass filter with the time constant T_w high enough to allow signals associated with oscillations in generator active power P_e to pass unchanged. The value of T_w is not critical and may be in the range of 1 to 20 seconds [2]. The considered controlled plant is not ASPR. To assure necessary conditions the supplementing of the controlled plant with the dynamic feedforward compensator must be performed.

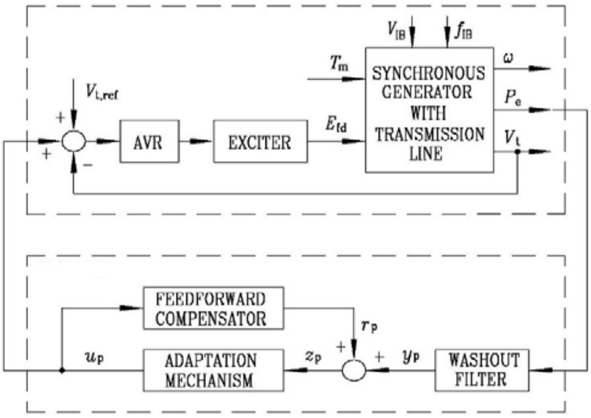

Fig. 2 Block diagram of the direct adaptive control power system stabilizer

V. RESULTS

For the analysis and design of the PSS the simplified linearized model is used. The proposed direct adaptive control power system stabilizer is tested with the non-linear seventh order model of a synchronous generator. MATLAB/Simulink tools were used for the simulations.

The synchronous generator with the nominal power 160 MVA is used for the simulations (the data in [1]). Input´s time responses are the same in all tests. Their traces for the nominal operating point are shown in Fig. 3. As it can be seen in Fig. 4, the response of the generator without power system stabilizer is poorly damped; hence it is inevitable to use the power system stabilizer.

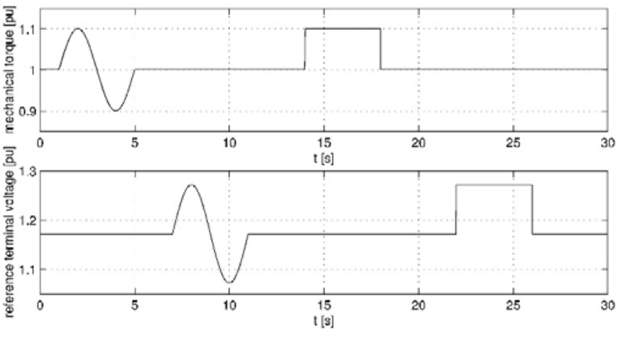

Fig. 3 Mechanical torque T_m and reference terminal voltage $V_{t,ref}$

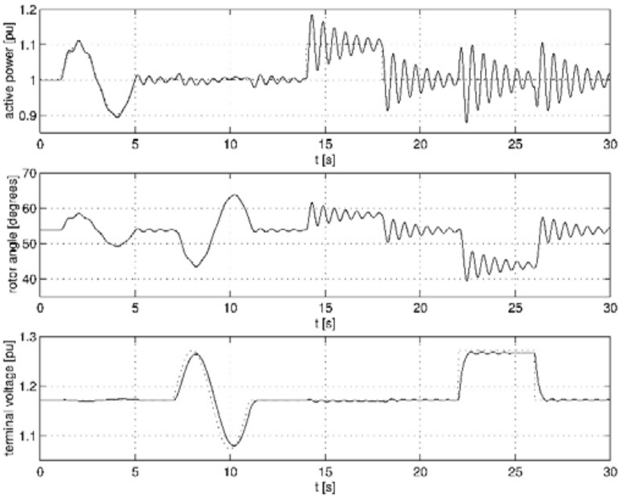

Fig. 4 Generator active power P_e, rotor angle δ and terminal voltage V_t in the nominal operating point without power system stabilizer

Figs. 5 and 6 show the synchronous generator behavior under small-signal disturbances (inputs are shown in Fig. 3):

- with direct adaptive control power system stabilizer in the nominal operating point $P_e = 1.0$ [pu], cos $\varphi = 0.85$, which correlates to the dominant eigenvalues of the system matrix: $p_{1,2} = -0.49 \pm j\ 10.67$,
- with direct adaptive control power system stabilizer in the operating point P_e = 1.25 [pu], cos φ = 0.95, which correlates to the dominant eigenvalues of the system matrix: $p_{1,2} = +0.0.033 \pm j\ 10.30$ (unstable).

The proposed direct adaptive control power system stabilizer assures the damping improvement in the complete operating range.

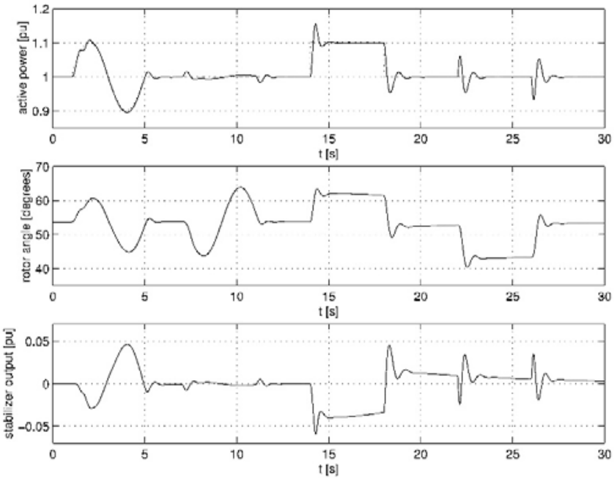

Fig. 5 Generator active power P_e, rotor angle δ and stabilizer output u_p in the nominal operating point with direct adaptive control power system stabilizer

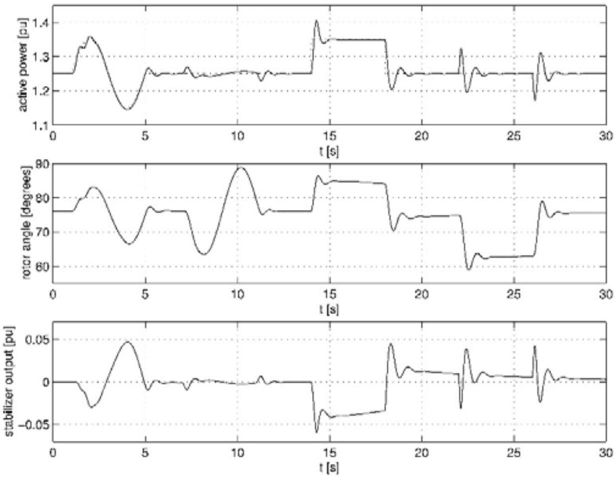

Fig. 6 Generator active power P_e, rotor angle δ and stabilizer output u_p for weak damped conditions in operating point P = 1.25 [pu], cos φ = 0.95 with direct adaptive control power system stabilizer

VI. CONCLUSION

The purpose of this paper is the development of the controller for damping of oscillations of the synchronous generator connected to the electric network. The stability problems of the synchronous generators and power systems are very suitable for the use of different algorithms of advanced control theories. The presented paper discusses the improvement of the synchronous generator's stability by means of power system stabilizer based on model reference adaptive control theory. The presented power system stabilizer has many advantages when compared with conventional stabilizers. The main improvements are: simple control algorithm (not time consuming), proved stability of the control system and satisfactory damping in all operating conditions. The results show essential improvement of stability.

The main contributions of the paper are:

- The synchronous generator´s analysis shows that the classical power system stabilizer does not assure the damping of the synchronous generator's oscillations in the entire operating area,
- It was presented that the model reference adaptive control theory is appropriate for development of the adaptive power system stabilizer.

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