

Adaptive Control for Power System Stability Improvement

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1. Introduction

The basic function of an excitation system is to provide a direct current to the synchronous generator field winding. In addition, the excitation system performs control and enables protective functions essential for the satisfactory operation of the power system by controlling the field voltage and thereby the field current. The control functions include the control of voltage and reactive power flow, and the enhancement of system stability. Because of the generator stator voltage control loop, the excitation system essentially changes the synchronous generator dynamics. Under certain loading conditions the entire system becomes unstable. Therefore, subsystem, which is called 'power system stabilizer (PSS)', is used to improve the dynamics of the complete system. The basic function of the PSS is to add damping to the rotor oscillations by controlling its excitation using an auxiliary stabilizing signal.

Linear control theory is still commonly used for the design of a conventional power system stabilizer with fixed parameters (CONV PSS) (Demello & Concordia, 1969; Anderson & Fouad, 1977; Bergen, 1986; Kundur, 1994; Machowsky et al., 2008). The necessary mathematical representation of a synchronous generator is given by a simplified linear model (SLM), which satisfactorily describes the behaviour of the machine in the vicinity of the operating point (Heffron & Phillips, 1952). A CONV PSS is simple to realize, but its application shows non-optimal damping through the entire operating range - by varying the loading, also the synchronous generator dynamic characteristics vary; the fact due to which the stabilizer determined in the nominal operating point does not assure the optimal damping in the entire operating range (Ritonja et al., 2000).

The stabilization of the synchronous generator has represented an attractive problem for testing different concepts of the modern control theory. The majority of the contributions have presented the application of adaptive control, robust control (Chow et al., 1990), variable structure control (Subbarao & Iyer, 1993), fuzzy control (Hassan & Malik, 1993), artificial neural network (Zhang et al., 1993), feedback linearization (Mielczarski & Zajackowski, 1994), and internal model control (Law et al., 1994). The presented research has been focused to the study of adaptive stabilization methods.

The adaptive control has been used in order to assure the optimal damping through the entire generator operating range. The use of the adaptive control is possible because the loading variations and consequently the variations of the synchronous generator dynamic characteristics are, in most cases, essentially slower than the adaptation mechanism.

The simplest, the oldest and the most tested adaptive approach is gain scheduling. In this case, the gain of the stabilizer is set with respect to the selected operating point. The main disadvantage of such approach is a rather time-consuming determination of the adequate loading schedule for the complete operating range. The gain scheduling represents an introductory step to real adaptive systems because of the gain setting being performed in open-loop fashion.

The first real adaptive approach to the stabilization of a synchronous generator is the self tuning control (STC). In this case, the calculation of parameters of the adequate discrete controller is based on the identified parameters of the SLM obtained by one of the parametric identification methods. The beginning of the self tuning PSS go back in 1979 (Ledwich, 1979). The combination of the recursive least square identification method and the pole shifting controller proved to be the most successful (Cheng et al., 1986). A disadvantage of such indirect approach is inconsistency in assuring the stability of the complete adaptive system. The stability of self tuning adaptive systems is assured only in case of simpler, less applicable, controller synthesis methods. Additional difficulties are caused by disturbances and non-modelled dynamics.

Direct model reference adaptive methods (direct MRAC) do not show these disadvantages; their design and the design of the belonging adaptation mechanism is based on assuring the stability of a complete adaptive system. Unfortunately, the synchronous generator with its specific nonlinear behavior does not allow a simple application of adaptation mechanisms of direct model reference systems.

Almost all MRAC methods are developed from one of the following approaches (Kaufman et al., 1993):

- adaptive control based on the full-state access method, which requires that all the state variables of the controlled plant are measurable (MRAC-FSA) (Landau, 1979) ,
- adaptive control based on the input-output description of a controlled plant, which can be divided into:
 - adaptive control where an adaptive observer is incorporated into the controller to overcome the inability to access the entire state space vector (MRAC-AO) (Narendra & Annaswamy, 1989) and
 - adaptive control for almost strictly positive real plants (MRAC-ASPR), called also command generator tracker concept (CGT) (Kaufman et al., 1993).

For the needs of PSS, the MRAC-FSA algorithms have proved to be less adequate. Reference (Irving et al., 1979) represents one of the first papers where the MRAC-FSA approach is used for stabilization. Difficulties in applying this concept are found especially in the unmeasurability of the necessary state space variables, which results in the unfulfillment of the Erzberger's perfect model following conditions (Landau, 1979). Not all state space variables of a synchronous generator are measurable, therefore a simplified linearised model, whose state variables can be measured, is used for the design. When using a model which considers the exciter dynamics, Erzberger's conditions are not fulfilled, i.e. perfect model following control cannot be obtained.

For the MRAC-AO implementation one should also be familiar with the structure of the controlled plant. The assumptions, which are required to assure the existence of an asymptotic stable solution, are found in (Narendra & Annaswamy, 1989). CONV PSS control structures cannot be directly extended to the MRAC-AO PSS because a controlled plant does not fulfil the required assumptions. Modifications in the structure of the power system stabiliser, as well as changes in adaptive law, were needed for a complete solution.

One of the implementations of MRAC-AO methods for the stabilisation of a synchronous generator is presented in (Ritonja et al, 1995).

MRAC-ASPR (or CGT) is more recent than the previously mentioned adaptive approaches. This approach is an output feedback method, which requires neither full state feedback nor adaptive observers. Other important properties of this class of algorithms are given as follows:

- they are applicable to non minimum phase systems and to multiple input and output systems,
- the order of the controlled plant needs not be known to select the reference model and the adaptation mechanism,
- the adaptation mechanism is computational undemanding

In this chapter, by studying the effects of the machine loading on the model dynamics, the reasons for the adaptive PSS are shown and the development and validation of the PSS based on MRAC-ASPR is described.

2. Mathematical model of the synchronous generator

The synchronous generator connected to an infinite bus is a multivariable nonlinear dynamic system described with the 7th order nonlinear state-space model. For the analysis and design of the control systems for synchronous machines, a simplified linearized third order model, which is called also Heffron-Phillips model, is the most popular. The model is described with equations (1) to (4):

$$T'_{d0} \dot{E}'_{q\Delta} = E_{FD\Delta} - K_4 \delta_{\Delta} - \frac{1}{K_3} E'_{q\Delta} \quad (1)$$

$$T_{e\Delta} = K_1 \delta_{\Delta} + K_2 E'_{q\Delta} \quad (2)$$

$$V_{t\Delta} = K_5 \delta_{\Delta} + K_6 E'_{q\Delta} \quad (3)$$

$$\frac{2H}{\omega_r} \ddot{\delta}_{\Delta} = T_{m\Delta} - T_{e\Delta} - D\omega_{\Delta} \quad (4)$$

where T_m represents the mechanical torque [pu], T_e represents 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 representing the total lumped damping effects from the damper windings [pu], ω_r is the synchronous speed [rad s⁻¹], T_{do}' is the direct axis transient open circuit time constant [s], $K_1 \dots K_6$ are the linearization parameters, s is the Laplace variable and the subscript Δ denotes the small signal incremental quantities.

Fig. 1 shows the block diagram of the Heffron-Phillips model.

2.1 Synchronous generator without voltage control

By varying the operating point, the parameter values K_1 through K_6 also vary. For the stability analysis the parameters K_1 to K_6 are not sufficiently transparent. The Heffron Phillips model is a 3rd order linear model whose characteristic polynomial has 2 complex

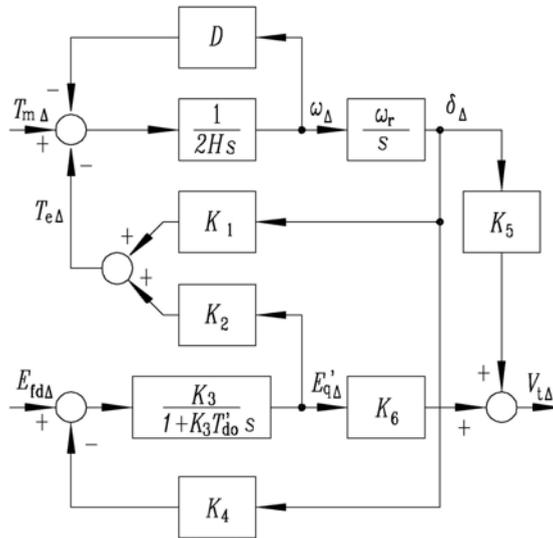


Fig. 1. Simplified linearized model of the synchronous generator connected to an infinite bus conjugate roots and 1 real root. The influence of the machine loading on the synchronous generator dynamic characteristics can be evaluated by eigenvalue loci analysis. The dominant complex conjugate eigenvalues are especially interesting for the dynamic stability analysis. They are directly related to the period and damping ratio of the rotor angle oscillation. The results of the numerical eigenvalue analysis of a typical 160 MVA turbogenerator are presented. The turbogenerator has following parameters:

$S_n=160$ MVA	$U_n=15$ kV	$\cos \varphi_n=0.85$	$T'_{d0}=5.9$ s
$x_d=1.7$ [pu]	$x'_d=0.245$ [pu]	$x_q=1.64$ [pu]	
$R_e=0.02$ [pu]	$X_e=0.02$ [pu]	$D=2$ [pu]	$H=3.96$ s

Table 1. Data for 160 MVA turbogenerator

where S_n is the nominal power, U_n the nominal stator voltage, $\cos \varphi_n$ the nominal power factor, x_d the direct axis reactance of the generator, x_q the quadrature axis reactance, x'_d the direct axis transient reactance, R_e , X_e the resistance and the reactance of the transmission line.

Fig. 2 shows the dominant complex conjugate eigenvalue loci of a turbogenerator as the function of the loading. The individual curves correspond to the constant reactive power. The active power P has varied in the range from 0.0 to 1.2 [pu] at the reactive power Q values from 0.0 to 1.2 [pu] in steps of 0.1 [pu]. The inductive generator load has been presumed. From Fig. 2 it is evident:

- by the increase of the active power the oscillation damping also increases,
- by the increase of the reactive power the natural frequency also increases.

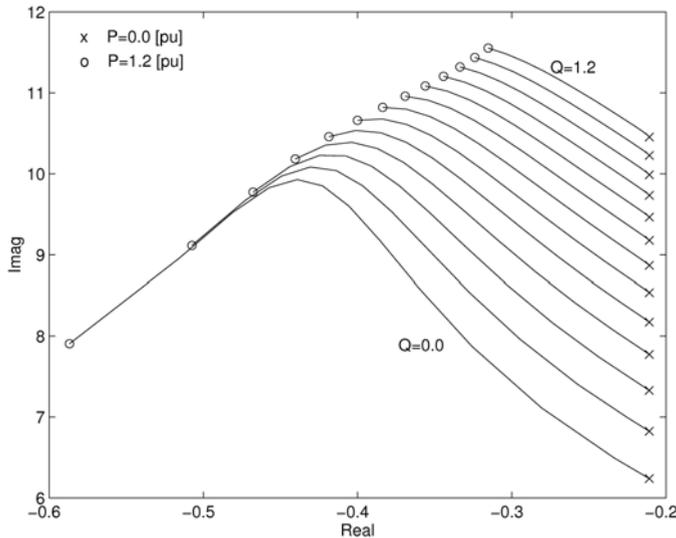


Fig. 2. Conjugate eigenvalue loci as a function of loading, turbogenerator, 160 MVA

2.2 Synchronous generator with voltage control

Automatic voltage regulator (AVR) with voltage control loop essentially changes the synchronous generator dynamics. The simplest model of the AVR with exciter is a first order lag, described with the transfer function:

$$\frac{E_{FD\Delta}(s)}{V_{t\Delta ref}(s) - V_{t\Delta}(s)} = \frac{k_{AVR}}{sT_{AVR} + 1}, \tag{5}$$

where $V_{t\Delta ref}$ represents the reference terminal voltage [pu], k_{AVR} represents the exciter and the voltage controller gain and T_{AVR} represents the exciter time constant [s]. The time constant T_{AVR} depends on the selected exciter while the gain k_{AVR} is selected so that the nonequation $k_{AVR} < T_{d0}/(2 T_{AVR})$ is fulfilled. In this way the sufficient damping of the voltage control loop is assured. Fig. 3 shows the voltage control system.

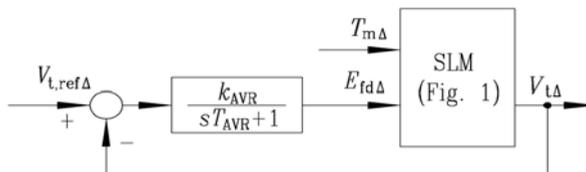


Fig. 3. Block diagram of SLM with voltage control

The linearized model of a synchronous generator with the voltage control system has four eigenvalues. The dominant complex conjugate eigenvalues are especially interesting. The results of the numerical eigenvalue analysis of a typical 160 MVA turbogenerator with adequate voltage control system are presented. Fig. 4 shows the dominant complex

conjugate eigenvalue loci of a turbogenerator with the voltage control system as the function of the loading. The individual curves correspond to the constant reactive power. The loading variation is the same as in case of an uncontrolled generator (Fig. 2). The selected exciter has had the time constant $T_{AVR} = 0.05$ s. The corresponding controller gain has been calculated according to the equation $k_{AVR} = 0.9 T_{d0} / (2 T_{AVR})$.

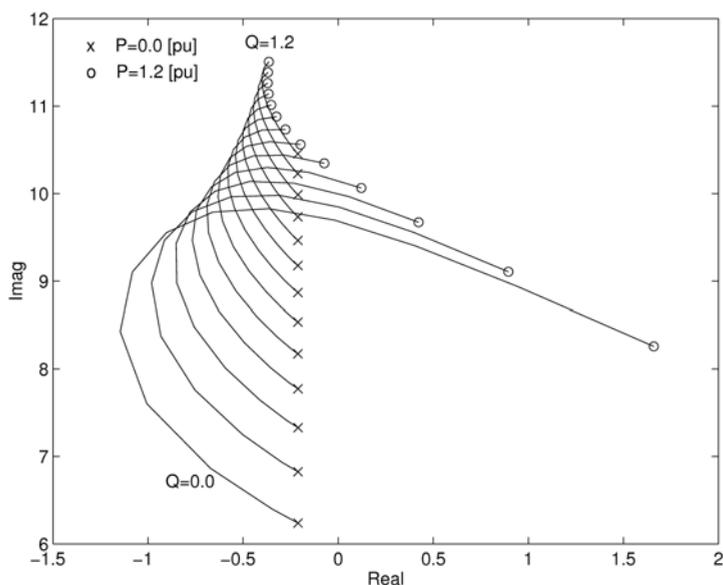


Fig. 4. Conjugate eigenvalue loci as a function of loading, turbogenerator with voltage control system, 160 MVA

In Fig. 4. the convexity of the constant Q -curves, which is characteristic of turbogenerators, is clearly evident. The convexity of curves increases with the decrease of the reactive power. Fig. 5 shows the dominant complex conjugate eigenvalue loci of a hydrogenerator as the function of the loading. The hydrogenerator has following parameters:

$S_n=158$ MVA	$U_n=13.8$ kV	$\cos \varphi_n=0.90$	$T'_{d0}=5.2$ s
$x_d=0.92$ [pu]	$x'_d=0.3$ [pu]	$x_q=0.51$ [pu]	
$R_e=0.02$ [pu]	$X_e=0.02$ [pu]	$D=2$ [pu]	$H=3.18$ s s

Table 2. Data for 158 MVA hydrogenerator

The loading variation, exciter and the voltage controller calculation is the same as in case of the analysed turbogenerator (Fig. 4).

After the numerical analysis of many typical turbo- and hydrogenerators of the nominal power between 9 MVA and 911 MVA, the region borders of the dominant complex conjugate eigenvalues has been calculated. The angle ψ denotes the deviation from the negative real axis and it is related to oscillations damping, whereas the natural frequency ω_0

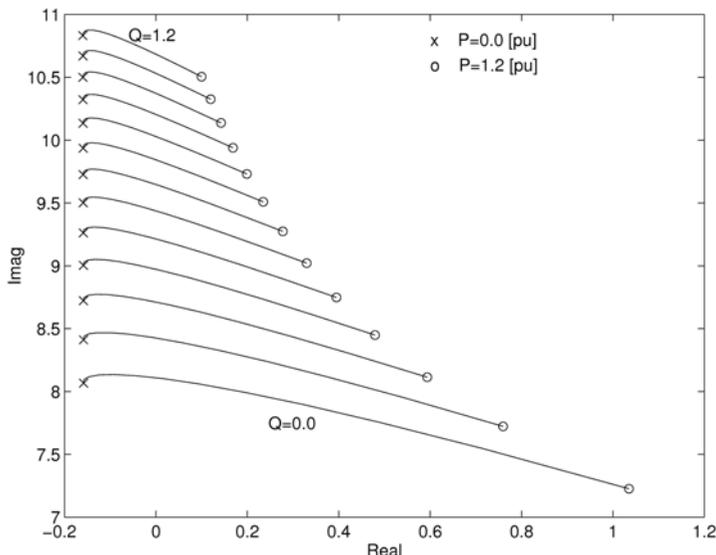


Fig. 5. Conjugate eigenvalue loci as a function of loading, hydrogenerator with voltage control system, 158 MVA

represents the distance from the origin and it is directly related to the oscillation frequency. Tables 3 and 4 show the region borders of dominant eigenvalues of the studied synchronous generators without and with the voltage control, respectively. It is evident that the voltage control loop with automatic voltage regulator greatly reduces oscillations damping.

	$\Psi_{\min}(\text{°})$	$\Psi_{\max}(\text{°})$	$\omega_{0,\min}(\text{s}^{-1})$	$\omega_{0,\max}(\text{s}^{-1})$
turbogenerators	79.9	89.6	3.8	17.3
hydrogeneratos	85.3	89.6	3.7	18.3

Table 3. The damping ratio and the natural frequency of complex conjugate eigenmodes of synchronous generators without voltage control loop

	$\Psi_{\min}(\text{°})$	$\Psi_{\max}(\text{°})$	$\omega_{0,\min}(\text{s}^{-1})$	$\omega_{0,\max}(\text{s}^{-1})$
turbogenerators	83.5	90.9	4.6	17.3
hydrogeneratos	88.6	92.4	4.6	18.3

Table 4. The damping ratio and the natural frequency of complex conjugate eigenmodes of synchronous generators with voltage control loop

From the analysis of the effect of different loadings on the synchronous generator dynamic characteristics can be concluded that the variations in the machine dynamics are considerable and therefore, an implementation of the adaptive power system stabilizer is meaningful.

3. MRAC based on command generator tracker theory

For the stabilization of the synchronous generator, the direct adaptive control (DAC) is used. The applied DAC procedure represents a simplified version of the MRAC based on command generator tracker theory (MRAC-CGT) (Kaufman et al., 1993).

The MRAC-CGT is considered for the controlled plant, which is described by

$$\dot{\mathbf{x}}_p(t) = \mathbf{A}_p \mathbf{x}_p(t) + \mathbf{B}_p \mathbf{u}_p(t) \quad (6)$$

$$\mathbf{y}_p(t) = \mathbf{C}_p \mathbf{x}_p(t) \quad (7)$$

where $\mathbf{x}_p(t)$ is the plant state vector, $\mathbf{u}_p(t)$ is the control vector, $\mathbf{y}_p(t)$ is the plant output vector, and \mathbf{A}_p , \mathbf{B}_p and \mathbf{C}_p are matrices of appropriate dimensions.

It is assumed that:

- the range of the plant matrices parameters is bounded,
- all possible pairs \mathbf{A}_p and \mathbf{B}_p are controllable and output stabilizable,
- all possible pairs \mathbf{A}_p and \mathbf{C}_p are observable.

The reference model is described by

$$\dot{\mathbf{x}}_m(t) = \mathbf{A}_m \mathbf{x}_m(t) + \mathbf{B}_m \mathbf{u}_m(t) \quad (8)$$

$$\mathbf{y}_m(t) = \mathbf{C}_m \mathbf{x}_m(t) \quad (9)$$

where $\mathbf{x}_m(t)$ is the model state vector, $\mathbf{u}_m(t)$ is the model command vector, $\mathbf{y}_m(t)$ is the model output vector and \mathbf{A}_m , \mathbf{B}_m and \mathbf{C}_m are matrices of appropriate dimensions. The model is assumed to be stable. The dimension of the model state may be less than the dimension of the plant state.

The output tracking error is defined as

$$\mathbf{e}_y(t) = \mathbf{y}_m(t) - \mathbf{y}_p(t) \quad (10)$$

The control $\mathbf{u}_p(t)$ for the plant output vector $\mathbf{y}_p(t)$ to approximate "reasonably well" 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 generated by the adaptive algorithm

$$\mathbf{u}_p(t) = \mathbf{K}_e(t) \mathbf{e}_y(t) + \mathbf{K}_x(t) \mathbf{x}_m(t) + \mathbf{K}_u(t) \mathbf{u}_m(t) \quad (11)$$

$$\mathbf{u}_p(t) = \mathbf{K}(t) \mathbf{r}(t) \quad (12)$$

where

$$\mathbf{K}(t) = [\mathbf{K}_e(t), \mathbf{K}_x(t), \mathbf{K}_u(t)] \quad (13)$$

$$\mathbf{r}^T(t) = [\mathbf{e}_y^T(t), \mathbf{x}_m^T(t), \mathbf{u}_m^T(t)] \quad (14)$$

The adaptive gains $\mathbf{K}(t)$ are obtained as a combination of the "proportional" and "integral" terms

$$\mathbf{K}(t) = \mathbf{K}_p(t) + \mathbf{K}_I(t) \quad (15)$$

$$\mathbf{K}_p(t) = \mathbf{e}_y(t) \mathbf{r}^T(t) \mathbf{T} \quad (16)$$

$$\dot{\mathbf{K}}_I(t) = \mathbf{e}_y(t) \mathbf{r}^T(t) \bar{\mathbf{T}} - \sigma \mathbf{K}_I(t) \quad (17)$$

where σ -term is introduced in order to avoid divergence of the integral gains in the presence of disturbance, \mathbf{T} and $\bar{\mathbf{T}}$ are positive definite and positive semi-definite adaptation coefficient matrices, respectively. The necessary condition for asymptotic tracking when $u_m(t)$ is a step command is

- the existence of a solution to the MRAC-CGT equation and
- the existence of the feedback gain \mathbf{K}_e (not needed for implementation) so that

$$\mathbf{H}(s) = \mathbf{C}_p (s\mathbf{I} - \mathbf{A}_p + \mathbf{B}_p \mathbf{K}_e \mathbf{C}_p)^{-1} \mathbf{B}_p \quad (18)$$

is strictly positive real. In this case the controlled plant is said to be almost strictly positive real (ASPR).

When the number of inputs is greater than or equal to the number of outputs, the solutions of MRAC-CGT equation almost always exists.

If the controlled plant is not ASPR, the augmenting of the plant with parallel dynamics such that the augmented plant is ASPR is suggested. In this case the previously described adaptive controller may be utilized.

For the non-ASPR plant described by the transfer matrix

$$\mathbf{G}_p(s) = \mathbf{C}_p (s\mathbf{I} - \mathbf{A}_p)^{-1} \mathbf{B}_p \quad (19)$$

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

$$\dot{\mathbf{s}}_p(t) = \mathbf{A}_s \mathbf{s}_p(t) + \mathbf{B}_s \mathbf{u}_p(t) \quad (20)$$

$$\mathbf{r}_p(t) = \mathbf{D}_s \mathbf{s}_p(t) \quad (21)$$

Instead of the plant output $\mathbf{y}_p(t)$ augmented output $\mathbf{z}_p(t)$ is to be controlled:

$$\mathbf{z}_p(t) = \mathbf{y}_p(t) + \mathbf{r}_p(t) \quad (22)$$

The augmented system is defined as

$$\mathbf{G}_a(s) = \mathbf{G}_p(s) + \mathbf{R}_p(s) \quad (23)$$

The feedforward compensator $\mathbf{R}_p(s)$ is an inverse of a (fictitious) stabilising controller for the plant, and must be selected such that the resulting relative degree of the augmented plant $\mathbf{G}_a(s)$ is indeed 1: For example, if a plant $\mathbf{G}_p(s)$ is stabilisable by PD controller, one can use its inverse that is just a simple first-order low-pass filter.

4. PSS based on direct adaptive control

The block diagram of the excitation system with the DAC stabilizer and inner automatic voltage regulation (AVR) loop is shown in Figure 6.

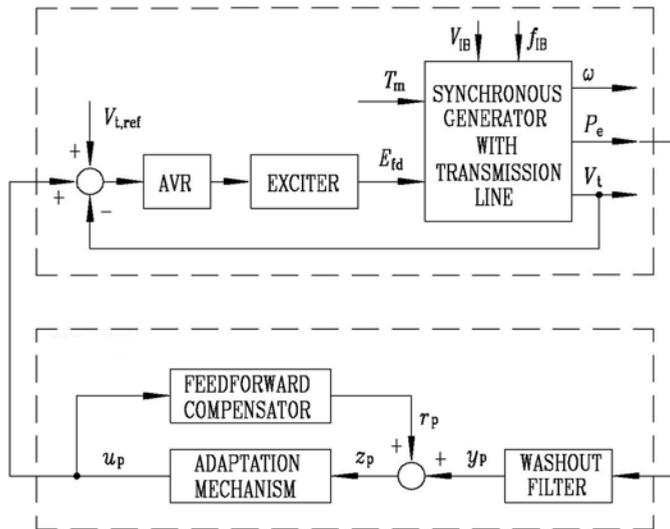


Fig. 6. Block diagram of the DAC-PSS structure

The benefit of the control diagram shown in Fig. 6 if compared to other adaptive structures is a very simple realization of the adaptation mechanism. The presented DAC-PSS is essentially simplified; because of the constant (zero) command signal, a reference model is namely not required.

The reference terminal voltage $V_{t,ref}$ and the mechanical torque T_m represent the main disturbances which affect the synchronous generator dynamics. The variations of the synchronous generator loading can be treated as a controlled plant parameters perturbations. The washout filter is a part of the controlled plant. Such controlled plant does not satisfy the necessary ASPR conditions, therefore the augmenting of the controlled plant with the parallel feedforward compensator must be carried out. Adaptation mechanism is described by equations 11 to 17.

5. Simulation results

For the analysis and design of the power system stabilizer the simplified linear model of the synchronous generator is used.

Simulation results given on the basis of the simplified linear model, show the applicability of the DAC-PSS for small-signal disturbances and parameters perturbations rejections. But the simplified linear model does not include the effects of the synchronous generator, which could be restrictive for the usage of the adaptive control, basically designed for linear plants.

In order to examine the influence of

- non-modeled dynamics and
- nonlinearities

the proposed DAC-PSS is tested with a non-linear seventh order model of a synchronous generator (Machowsky et al., 2008).

The typical 160 MVA synchronous generator is considered. Dynamics of the system inputs are the same in all cases. Their traces for the nominal operating point are shown in Fig. 7. As

it can be seen in Fig. 8, the response of the generator without PSS is poorly damped; hence it is inevitable to use the PSS.

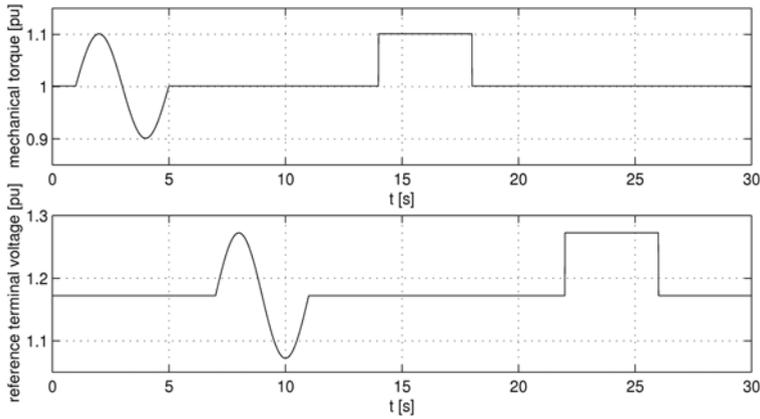


Fig. 7. Mechanical torque T_m and reference terminal voltage $V_{t,ref}$

The adaptive controller consists of feedforward compensator, adaptation mechanism and washout filter.

The feed forward augmentation was defined as

$$\frac{r_p(s)}{u_p(s)} = \frac{k_{ff}}{sT_{ff} + 1}, \tag{24}$$

and k_p and k_i denote proportional and integral gain,

$$k_p = T, \quad k_i = \bar{T}, \tag{25}$$

The parameters of the control system are shown in the Table 5:

Feedforward compensator:	$k_{ff}=1$	$T_{ff}=0.1$ s	
Washout filter time constant:	$T_w=10$ s		
Adaptation mechanism coefficients:	$k_p=1$	$k_i=100$	$\sigma=0.1$

Table 5. Control system data

The control system parameters k_{ff} , T_{ff} , k_p , k_i and σ were obtained using systematic analysis.

Fig. 9 and Fig. 10 show the synchronous generator behavior under small-signal disturbances:

- with DAC-PSS in the nominal operating point $P=1.0$ [pu], $\cos \varphi = 0.85$, which corresponds to the dominant eigenvalues $p_{1,2}=-0.49 \pm j 10.67$,
- with DAC-PSS in the operating point $P=1.25$ [pu], $\cos \varphi = 0.95$, which corresponds to the dominant eigenvalues $p_{1,2}=+0.033 \pm j 10.30$ (unstable)

The proposed DAC-PSS assures the damping improvement in the complete operating range.

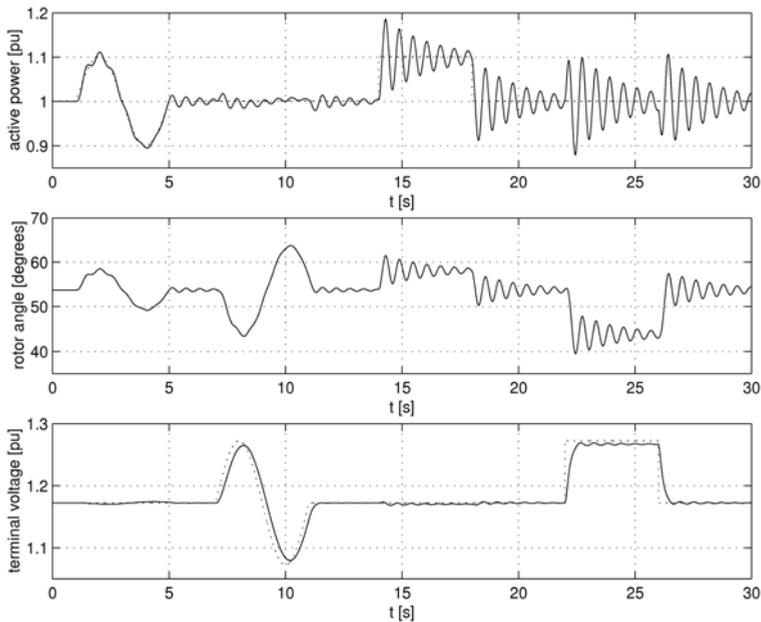


Fig. 8. Generator active power P_e , rotor angle δ and terminal voltage V_t in the nominal operating point without PSS

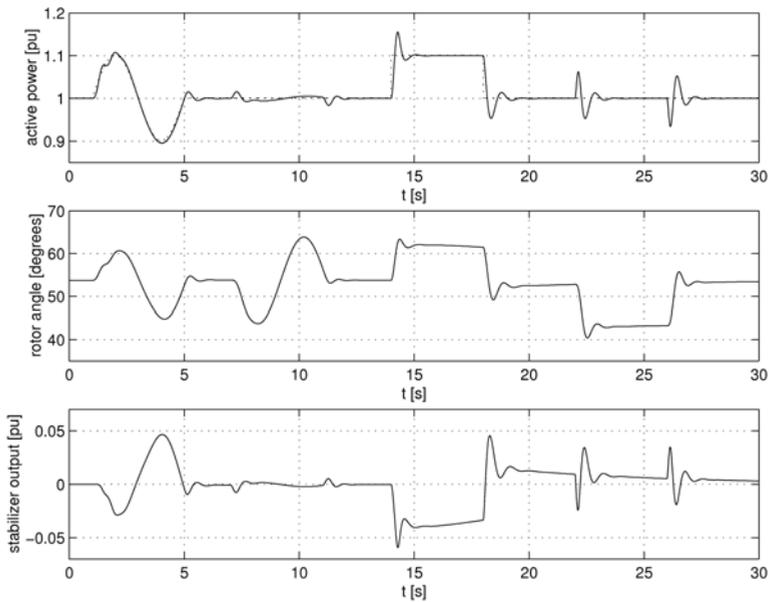


Fig. 9. Generator active power P_e , rotor angle δ and stabilizer output u_p in the nominal operating point with DAC-PSS

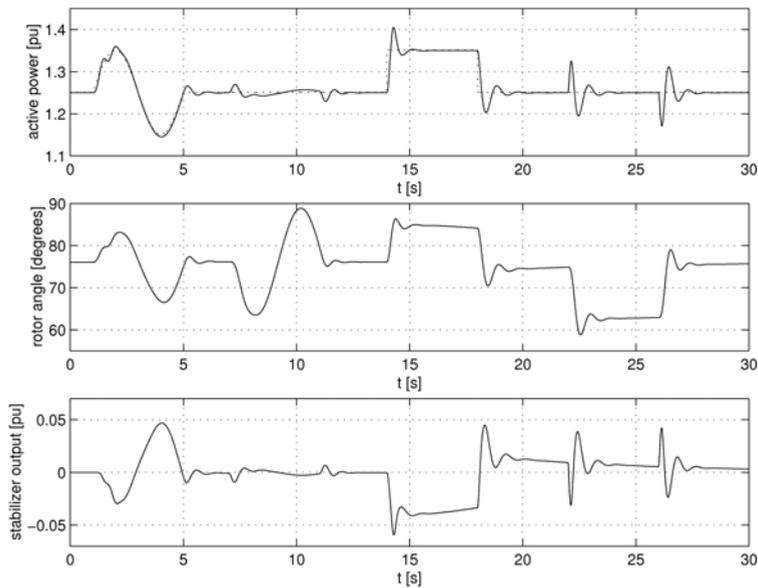


Fig. 10. Generator active power P_e , rotor angle δ and stabilizer output u_p in the unstable operating point $P=1.25$ [pu], $\cos \varphi = 0.95$ with DAC-PSS

The bursting phenomenon is notable from the simulation. In the case when the unstable controlled plant (operating point $P=1.25$ [pu], $\cos \varphi = 0.95$) has no disturbances during a long period of time, the system ends with oscillations of the active power and of the adaptive gain. The oscillations begin approximately at 1200 s after the last disturbance. To avoid the bursting phenomenon, $\mathbf{K}(t)$, obtained from equations (15) to (17) and used in equation (12), can be replaced by $\mathbf{K}(t)$, calculated from:

$$\mathbf{K}_{bf}(t) = \mathbf{K}(t) + \mathbf{K}_0 \quad (26)$$

where \mathbf{K}_0 is any constant output feedback gain that stabilizes the controlled plant ($\mathbf{K}_0 \geq \mathbf{K}_{\min}$). The bursting phenomenon is shown in Fig. 11.

6. Experimental results

The presented DAC-PSS is implemented on a lab size testing system, composed of a 35 kW DC motor with current control as prime mover, a 28 kVA synchronous generator, connected to the infinite bus, 3-phase 6-pulse thyristor exciter, active power and terminal voltage measuring units, necessary analog low pass filters and an PC with AD/DA peripherie card used for implementing AVR and PSS scheme. Disturbances are created by altering DC motor mechanical torque. Generator active power responses during the disturbances are recorded by PC.

Results show again that the DAC-PSS provides more effective and reliable damping. Diagram of the testing system is shown in Fig. 12, with measured testing results shown in Fig. 13.

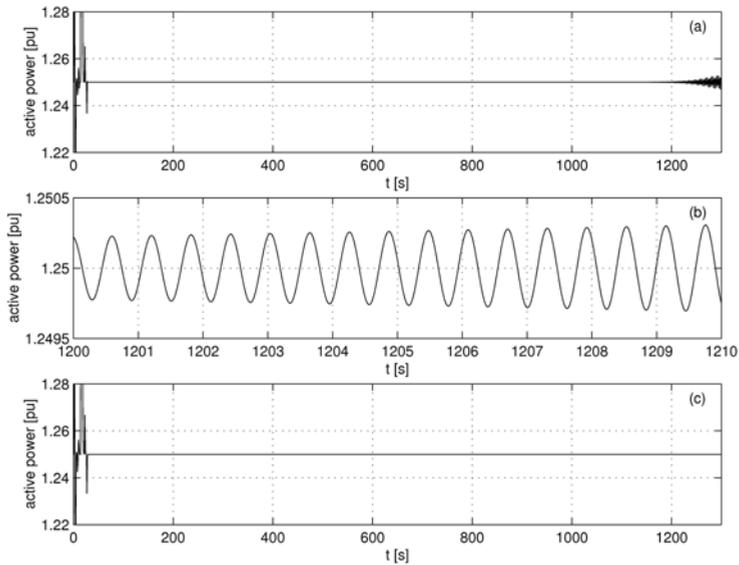


Fig. 11. Bursting phenomenon - generator active power P_e in the nominal operating point with DAC-PSS: a) $K_0=0$, b) $K_0=0$ (zoom) and c) $K_0=0.5$

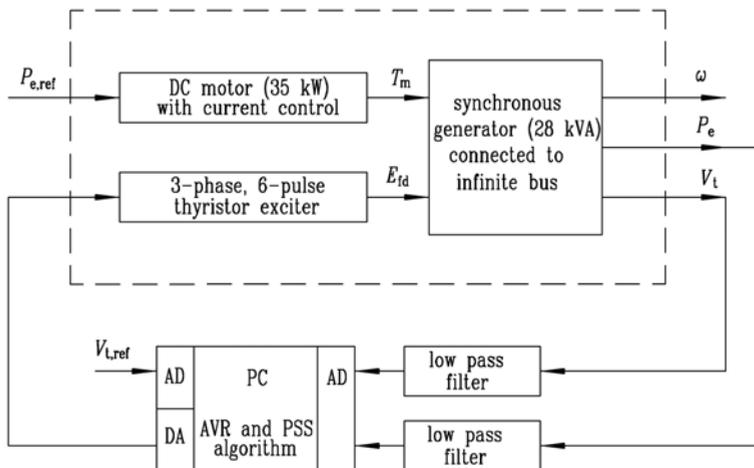


Fig. 12. Testing system block diagram

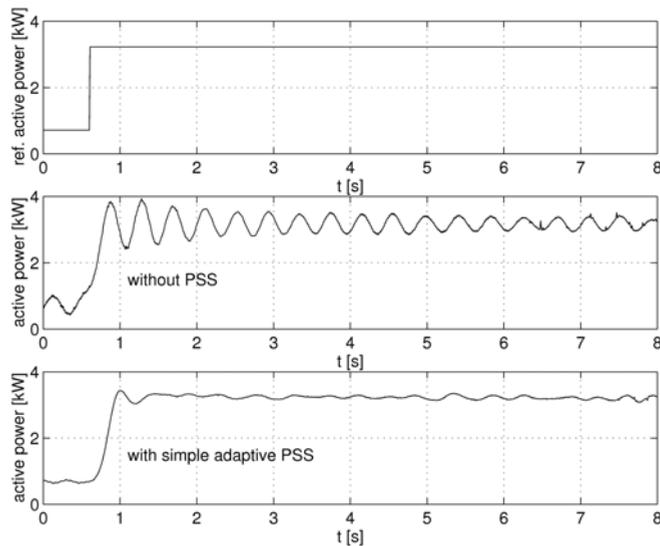


Fig. 13. Experimental results: the variation of the reference active power $P_{e,ref}$ and the generator active power P_e responses without PSS and with DAC-PSS

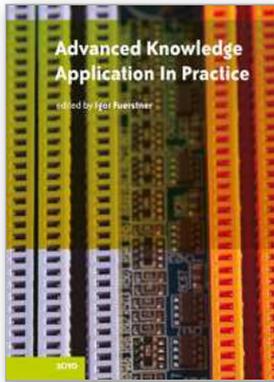
7. Conclusion

This chapter examines the synchronous generator stability and the implementation of the adaptive stabilizer based on direct adaptive control. The simplified linearised model eigenvalue analysis for the synchronous generator without and with voltage control loop show the insufficiency of the conventional stabilizer. The use of the developed adaptive stabilizer is recommended. The advantage of the presented concept is unsophisticated realization and optimal damping in entire operating range. The results of simulations and experiments show essential improvement of stability.

8. References

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