ANALYSIS AND DESIGN OF A ROBUST COORDINATED AVR/PSS

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Abstract — **A robust coordinated AVR/PSS, called the "Desensitized Four Loops Regulator" (DFLR) has been recently designed using the "desensitized control" theory. Its synthesis method (which can be applied to other problems than excitation control) and its structure are detailed in this paper. It is a state feedback controller including an integrator on the regulation error. This structure, although it is well known in the control community, is not usual for excitation control of generators (except in France). Hence, in order to make this approach more widely applicable in an industrial point of view, this controller is put, using approximations, in the standard AVR+PSS structure IEEE ST1A+PSS1A. The resulting AVR+PSS is proven to have a good performance, in particular for damping inter-area oscillations.**

Keywords — **AVR, PSS, Linear quadratic control, Desensitivity, Inter-area oscillations .**

I. INTRODUCTION

A. Excitation control of generators is a very important topic in the field of power systems. A good excitation control, indeed, has proven to be very efficient to support the voltage on the power system, to enhance its transient stability and to damp its oscillations (see, *e.g.*, [2], [5], [17], [18], [14]). In addition, this type of solution is much cheaper than heavy equipments like FACTS which are necessary only in very specific cases, as far as oscillation damping is concerned.

For damping oscillations, Automatic Voltage Regulators (AVRs) are not sufficient, and using Power System Stabilizers (PSSs) is necessary. Therefore, a good generator terminal voltage controller should combine an AVR with a PSS.

When designing an AVR+PSS, it is very important to take into account possible variations of the generator operating point. As a matter of fact, perturbations like load variations and line outages can occur. The AVR+PSS should not be destabilized, and even should retain a sufficiently high level of performance when those perturbations arise. In other words, the AVR+PSS should be sufficiently robust against system variations. It has been shown that for a combination of an AVR with a PSS to be robust, both of them should be coordinated [14], [9], *i.e.*, they should not be designed in an independent manner.

A robust coordinated AVR/PSS has been recently proposed [9]. This controller is called the "Desensitized Four Loops Regulator" (DFLR) and has been designed using the "desensitivity method" [13], [9]. It should replace the "Four Loops Regulator" [5] which has been implemented on the French power system for about 15 years.

The DFLR has been tested with EUROSTAG, a time simulation software for stability studies [15], and with the Électricité de France Transient Network Analyzer. It has proven to be a high-performance and robust controller. Representative time-domain simulations have been presented in [9]; they show that the DFLR is better (and, in particular, more robust) in the "single machine-infinite bus" case than a classical AVR+PSS. Another advantage of the DFLR is that the tuning of its parameters is very systematic and straightforward.

B. In this paper, it is shown that the DFLR can be put, using approximations, in the standard AVR+PSS structure IEEE ST1A + PSS1A. These approximations do not significantly deteriorate the performance of the controller. Hence, our approach is widely applicable in an industrial point of view. In addition, the resulting AVR+PSS is proven to well damp the local and inter-area oscillations of a multi-machine network.

C. The paper is organized as follows: the DFLR is presented in Section II, where the main ideas of [9] are briefly recalled and some points which were not detailed are explained, *e.g.*, the model augmentation and the structure of the DFLR. The design method proposed in Section II can be applied to any system subject to "parametric uncertainties"; hence, this approach is relevant to many kinds of plants, in particular in the field of power systems. In Section III, it is shown how the DFLR can be put in the standard AVR+PSS structure IEEE ST1A+PSS1A. In Section IV, the resulting

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controller is analyzed (i) in case of three phase fault (for a single machine - infinite bus system) and (ii) on a multi-machine system where inter-area oscillations are observed without PSS. The performance is good in both cases. Section V is devoted to concluding remarks.

II. A ROBUST COORDINATED AVR/PSS : THE DFLR

Although the design method proposed here is very general (see Section I.C), it is explained here in the specific case of an AVR+PSS synthesis.

A. Basic linear model

The model which is considered for the design is the classical system "single machine, infinite bus". This model is linearized around an operating point defined by specific values P*, V*, q* and X* of the active power P, the terminal voltage V, the reactive power q [1] and the external reactance X, respectively. That model is reduced to order 3 using the balanced realization technique, which can be viewed as a principal component analysis method for dynamical systems [16]. For any signal ζ, let $\delta\zeta$ denote the deviation of ζ from its steady-state value (when it exists). The state is chosen as being $z = [\delta V \;\; \delta P \;\; \delta\omega]^T$, where ω is the rotor speed; the control u is δV_e, where V_e is the excitation voltage (see, *e.g.*, [4], p. 203). The excitation system is assumed to be static. The variable to be controlled can be written $\delta V = C\, z$, with $C = [1 \;\; 0 \;\; 0]$.

Set $\Theta = [P^* \; V^* \; q^* \; X^*]^T$; the matrices of the linearized model depend on Θ, *i.e.*, the differential equation of the linearized system around the operating point Θ is of the form

$$\dot{z} = F(\Theta)\, z + G(\Theta)\, u \quad (1)$$

It is assumed that the vector of parameters Θ is constant with respect to time and unknown (thus, it is a considered as random vector) but belongs to a known domain *D*, called the "admissible parametric domain".

B. Augmented model [8]

Let V_C be the terminal voltage set-point (which is assumed to be constant). In order to meet the steady-state objective, the plant model (1) is augmented with the additional state e defined by

$$\dot{e} = V - V_c \quad (2)$$

With the control synthesized below, e(t) tends to a constant as t tends to infinity, thus the regulation error $V(t) - V_c$ tends to zero; as a result, the steady-state value of V(t) is V_c, so that $\delta V = V - V_c$. In addition, as e is defined up to a constant, one can set $\delta e = e$.

The "augmented state" is $x = [z^T \;\; e]^T$. Equations (1), (2) yield

$$\dot{x} = A(\Theta)\, x + B(\Theta)\, u \quad (3)$$

where $(A(\Theta),\; B(\Theta))$ is controllable [8] and is defined by

$$A(\Theta) = \begin{bmatrix} F(\Theta) & 0 \\ C & 0 \end{bmatrix} \quad B(\Theta) = \begin{bmatrix} G(\Theta) \\ 0 \end{bmatrix}$$

C. Desensitivity

Desensitivity is a method for designing a robust controller with respect to parametric uncertainties, *i.e.*, a controller stabilizing system (3) with a suitable level of performance, not only when Θ has its nominal value Θ_0, but for every Θ in *D*. In order to clarify the main idea of desensitivity, it is assumed in this section that Θ is a scalar parameter θ (although this is not true for the AVR+PSS design problem) and that the control law is constrained to have the form

$$u = -K\,x \quad (4)$$

1) The state x is a function of t and θ, and so is also the control u by (4), *i.e.*

$$x = x(t, \theta), \;\; u = u(t, \theta)$$

Let θ_0 be a nominal value of θ. Desensitivity consists in minimizing a quadratic index involving $x_0(t) = x(t, \theta_0)$, $u_0(t) = u(t, \theta_0)$, and also the partial derivatives $\xi_0(t) = \partial_\theta x(t, \theta_0)$ and $\mu_0(t) = \partial_\theta u(t, \theta_0)$ (where ∂_θ denotes the partial derivative with respect to θ); $\xi_0(t)$ and $\mu_0(t)$ are called the "sensitivities".
This index is defined by

$$J_\sigma = \int_0^\infty \left[x_0(t)^T Q x_0(t) + |u_0(t)|^2 + \sigma^2 \left[\xi_0(t)^T Q \xi_0(t) + |\mu_0(t)|^2 \right] \right] dt \quad (5)$$

where σ^2 is the variance of θ.
The minimization of the sensitivities ensures that the "perturbed trajectories" $x(t, \theta)$ and $u(t, \theta)$ remain close to the "nominal trajectories" $x_0(t)$ and $u_0(t)$ when the current parameter value θ is slightly different (and, in practice, rather different) from θ_0. In this manner, a good robustness of the performance is obtained. The larger is σ, the more weighted are the sensitivities, and the more improved is the robustness. The price to pay for this improvement, however, is a deterioration of the performance, so that a good compromise should be found.

2) Differentiating (4) with respect to θ yields $\mu_0(t) = -K\,\xi_0(t)$. Now, differentiating (3) with respect to θ and using the latter equation and as well as (3) one obtains

$$\frac{d}{dt}\begin{bmatrix} x_0 \\ \xi_0 \end{bmatrix} = \hat{A}_0 \begin{bmatrix} x_0 \\ \xi_0 \end{bmatrix} + \hat{B}_0\, u_0 \quad (6)$$

$$x_0 = \hat{C}_0 \begin{bmatrix} x_0^T & \xi_0^T \end{bmatrix}^T \quad (7)$$

where the expressions of $\hat{A}_0, \hat{B}_0, \hat{C}_0$ can be easily determined; the two former matrices depend on K. Thus, assuming that K is known, a controller can be synthesized for system (6), (7) using the LQG theory [1].

[1] This notation is not classic, but it allows one to avoid a confusion with the state weighting matrix (see (5)).

However, K is the controller gain matrix we want to calculate, hence iterations should be used.

At step 0, a first gain matrix K_0 is calculated, such that (4) stabilizes the nominal system (3) (with $\Theta = \theta_0$). For this, the classical LQ method [1] is used: the quadratic index (5) is minimized with $\sigma = 0$; the matrix Q is chosen diagonal; K_0 is the gain of the non-desensitized LQ regulator.

At step 1, the sensitivities are for the first time taken into account by choosing $\sigma>0$ (see [9] for the general case, where the variance σ^2 should be replaced by the covariance matrix Σ of Θ and where Kronecker products of matrices should be used). The resulting quadratic index is minimized for system (6), (7) with K replaced by K_0, using the LQG theory; the order of the LQG controller then obtained in nonzero, hence it is reduced to order zero[2]. In this manner, a first desensitized controller with gain matrix K_1 is obtained.

Step 1 can now be repeated with K_0 replaced by K_1, etc. In this manner a sequence of gain matrices (K_n) is determined. The procedure ends when $K_n = K_{n+1}$ up to the tolerance. The number of iterations does not generally exceed about 10.

D. DFLR description

1) In what follows, all quantities are expressed in p.u., and $\alpha = 1$ (resp. 2.4) in the French (resp. IEEE) reference, except for ω which is in rad/s, and X includes the reactance of the transformer. Let the admissible parametric domain D be:

$$P^* = 1, \quad 0.9 \le V^* \le 1.05,$$
$$-1 \le q^* \le 1, \quad 0.2 \le X^* \le 0.95$$

Notice that D is very large. The design point (*i.e.*, the nominal value of Θ) is chosen as being $\Theta_0 = [P^*\ V^*\ q^*\ X^*]^T = [1\ \ 0.95\ \ 1\ \ 0.40]^T$. For the 800 MW generator considered here, one has

$$A(\Theta)=\begin{bmatrix} -0.1151 & -0.0852 & -0.0835 & 0 \\ -0.3013 & -0.3730 & 0.0935 & 0 \\ -0.2237 & -29.2755 & -0.0035 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}, \quad B(\Theta) = (1/\alpha)\begin{bmatrix} 0.1267 \\ 0.3331 \\ 0.1227 \\ 0 \end{bmatrix}$$

Recall that the state is $x = [\delta V\ \delta P\ \delta\omega\ e]^T$ and that the input is $u = \delta V_e$.

2) The matrix Q is chosen as being

$$Q = \alpha^2\, \mathrm{diag}(800, 0, 5, 200)$$

The idea leading to this choice is the following: basically, only the states δV —the variable to be controlled— and e —the output of the integrator— are weighted, in order to obtain a good PI controller for the voltage regulation (i.e., a good proportionnal and integral AVR). The additional weight on $\delta\omega$ is rather small; its role is to slightly improve the damping at the design point.

The controller gain matrix (for $\Sigma = 0$) is

$$K_0 = \alpha\,[\ 32.4\ \ \ 9.2\ \ -1.85\ \ \ 14.1\ ]$$

The robustness of this controller is not sufficient, because the system is not stabilized in the whole admissible parametric domain D. Therefore, this controller should be desensitized.

3) The covariance matrix of Θ is chosen as being

$$\Sigma = \mathrm{diag}(\sigma_P^2, \sigma_V^2, \sigma_q^2, \sigma_X^2)$$

with $\sigma_P = 0$ and $\sigma_q = 0$; σ_V and σ_X are increased (starting from zero) until stability is obtained in the whole admissible parametric domain D, with sufficient modulus and delay margins (recall that the modulus margin is the distance between the Nyquist plot and the critical point −1 and that the delay margin is the smallest unmodelled delay which makes the closed loop unstable [6]). Note that this procedure is very systematic: the standard deviation σ_θ (θ = P, V, q or X) should be increased while the largest possible deviation of the parameter θ in D from its nominal value θ_0 causes instability (or, more precisely, insufficient modulus and delay margins).

Finally, σ_V and σ_X are found to be equal to 0.6 and 0.3, respectively, and after some iterations the following controller gain matrix is obtained:

$$K = \alpha\,[\ 32.3\ \ \ 17.9\ \ -3.37\ \ \ 13.2\ ] \triangleq [\ K_V\ K_P\ K_\omega\ K_e\ ] \quad (8)$$

Notice that, in comparison with K_0, the gains on δP and $\delta\omega$ have been almost doubled, whereas the other gains are roughly unchanged. See [7] for other remarks and more details about the effect of desensitivity.

4) The block-diagram of the DFLR is shown in Fig. 1[3]. Notice that the active power P has been replaced by the "accelerating power" $P - P_m$, where P_m denotes the mechanical power supplied by the turbine.

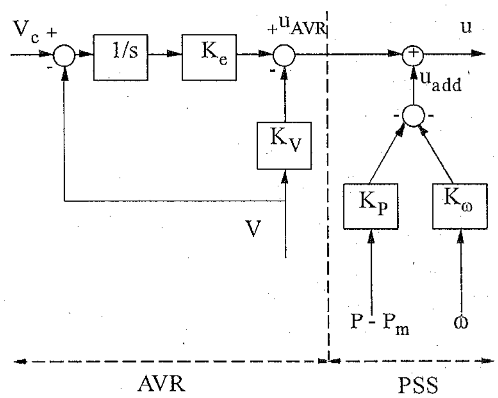

Fig. 1 block-diagram of the DFLR

[2] According to the authors' experience, that reduction to order zero does not significantly disturb the closed loop dynamics, as far as AVR+PSS design is concerned. However, in [9], that reduction to order zero is made at the final step only. The latter method is more accurate. The reduction to order zero is assumed to be made at each step here for the sake of simplicity.

[3] The shaft torsion oscillation filter presented in [10] can be connected in series to the ω-channel.

The block-diagram in Fig. 1 clearly shows that the DFLR can be viewed as a coordinated AVR/PSS (in the sense explained in Section I.A); u_{add} can indeed be viewed as an additional stabilizing signal. The gains K_V, K_p, K_ω and K_e are constant.

III. DETERMINATION OF THE STANDARD IEEE STRUCTURE

A. The AVR

1) The structure of the IEEE ST1A AVR is shown in Fig.2. Its transfer function is (with $T_b = T_a + T_f + K_a K_f$)

$$\mathrm{AVR1}(s) = \frac{K_a(1+sT_f)}{1+T_b s+T_a T_f s^2} \tag{9}$$

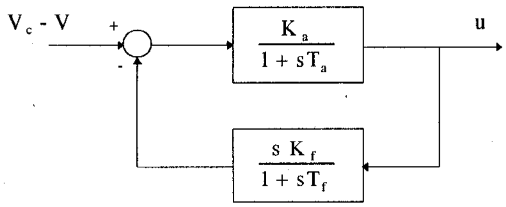

Fig.2 IEEE ST1A AVR

2) The transfer function of the AVR in Fig.1 is

$$\mathrm{AVR2}(s) = K_V + \frac{K_e}{s} \tag{10}$$

Its Bode plot is shown in Fig.3 (solid line), which shows how AVR2(s) can be approximated by a transfer function of the form

$$\mathrm{AVR3}(s) = \frac{K_a(1+T_f s)}{(1+T_p s)(1+T_s s)} \tag{11}$$

(dotted line) on a frequency band B = [$1/T_p$, $1/T_s$]. Finally, it is easy to put AVR3(s) in the form (9).

Therefore, for putting the AVR in Fig.1 in the structure of the AVR in Fig.2, the procedure is as follows (where all time constants are expressed in seconds):

(i) choose the frequency band B, *i.e.*, the time constants T_p and T_s; the frequencies are expressed in rad/s;

(ii) calculate

$$K_a = \left| K_V + \frac{K_e}{s} \right| \text{ with } s = \frac{i}{T_p} \quad (i = \sqrt{-1})$$

$$T_a = \frac{T_p T_s}{T_f}; \quad T_f = \frac{K_V}{K_e}; \quad K_f = \frac{(T_p + T_s) - (T_a + T_f)}{K_a}$$

Choosing T_P = 10 and T_s = 1/400 and using the gain matrix value (8), one obtains T_a = 0.01, T_f = 2.45, K_a = α 136, K_f = 0.055. Note the small value of T_a, which corresponds to the typical time constant of a fast exciter. As the delay margin is good (≥ 75 ms, see Section II.D.3), the controller is robust with respect to the actual value of the exciter, provided that it is sufficiently small.

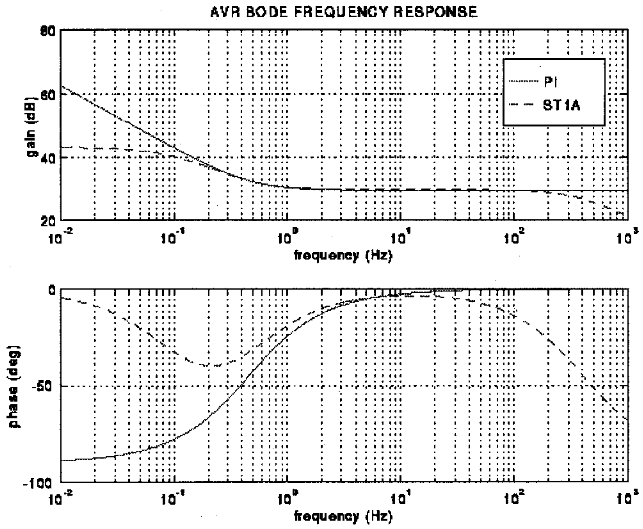

Fig.3 Bode diagram

B. The PSS

1) The structure of the IEEE PSS1A is shown in Fig.4 where P_a denotes the accelerating power P_m - P; the time constant T_5 is chosen much larger than the other ones (*e.g.*, T_5 = 30)[4], so that its transfer function is roughly

$$\mathrm{PSS1}(s) \cong K_s \cdot \frac{1+T_1 s}{1+T_2 s} \cdot \frac{1+T_3 s}{1+T_4 s} \tag{12}$$

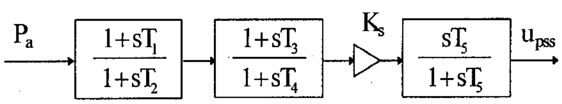

Fig.4 IEEE PSS1A PSS

The signal u_{pss} acts as is shown in Fig.5

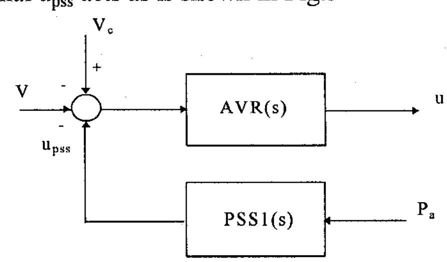

Fig.5 Classical AVR+PSS

[4] The value of T_5 is not critical [12]; T_5=30 is the lowest upper bound of the usual range [2, p. 339].

2) The additional stabilizing signal in Fig.1 is

$$u_{add} = -\left[K_{\omega}\omega + K_p(P - P_m)\right]$$

Using the electromechanical equation (written in the Laplace domain)

$$\omega(s) = \frac{1}{2Hs} P_a(s) \ ,$$

one obtains

$$u_{add}(s) = (K_p - \frac{K_{\omega}}{2Hs}) P_a(s) \ . \qquad (13)$$

Therefore, one has

$$u_{add}(s) \cong PSS2(s)\ P_a(s) \ , \qquad (14)$$

where, for a sufficiently large time constant $\tau > 0$,

$$PSS2(s) = K_p - \frac{K_{\omega}}{2H\,(s + 1/\tau)} \ . \qquad (15)$$

The comparison of the figures 1 and 5 yields

$$u_{pss}(s) = (AVR(s))^{-1} u_{add}(s) \ . \qquad (16)$$

From the Bode diagram in Fig.3, the transfer function AVR1(s) can be approximated by the biproper one

$$AVR1(s) \cong \frac{K_a(1 + T_f s)}{1 + T_p s} \ .$$

Hence, by (13), (14), (15) one obtains

$$PSS1(s) \cong \frac{1 + T_p s}{K_a(1 + T_f s)} PSS2(s) \ . \qquad (17)$$

The right-hand member of (17) is a second order transfer function which can be put in the form (12).
Choosing $\tau = 20$, one finally obtains $T_1 = 0.18$, $T_2 = 2.45$, $T_3 = 10$, $T_4 = 20$, $K_s = 14.5$ (recall that all time constants are expressed in seconds).

Remark: A similar rationale can be used for obtaining a PSS whose input is the rotor speed.

IV. ANALYSIS OF THE RESULTING AVR+PSS

A. Three phase fault (single machine, infinite bus)

Let us first consider the performance of the resulting AVR+PSS in the case of a 110 ms three phase fault when the machine is connected to an infinite bus at the following operating point: P=1, V=0.95, q=1, X=0.6 (hence, this fault is a very large disturbance). The behaviors of V, P, ω, and V_e are shown in Fig.6. The system remains stable. The excitation voltage remains at its highest value during almost 1 second after the fault clearing, and, as is well known, such an overexcitation is a key point for getting a good critical clearing time: see, e.g. [9]. Note that in the case shown here, no line is tripped after the fault clearing; but the controller is very efficient in the case of a switching operation [9], hence the case shown here can be considered as sufficiently representative.

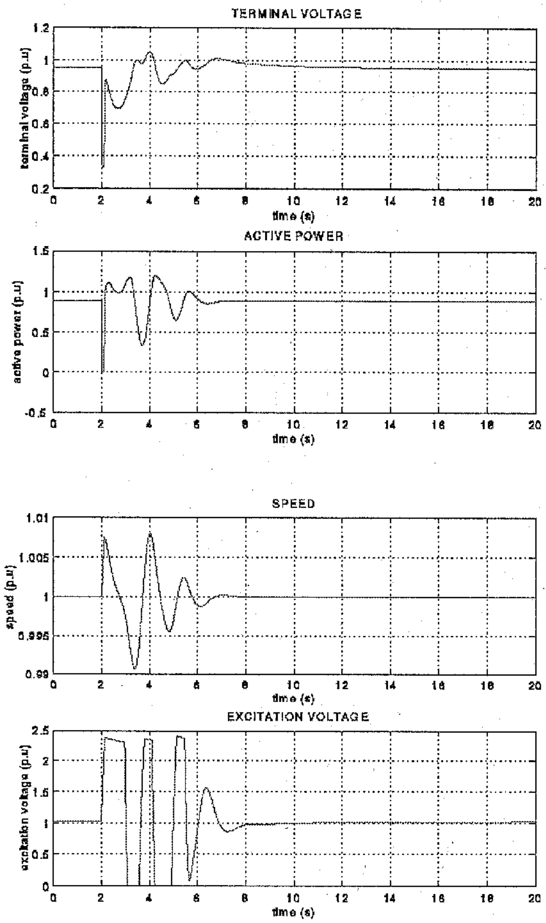

Fig.6 Three phase fault

B. Oscillation damping (multi-machine network)

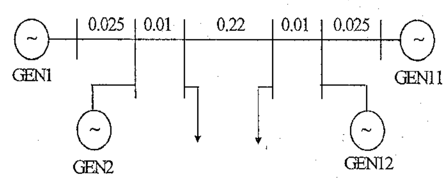

Fig.7 The multi-machine network

For testing the AVR+PSS on a multi-machine network, the system in Fig. 7, identical to the one defined in [11], has been considered. All generators have the characteristics detailed in [11]. One observes inter-area oscillations at roughly 0.35 Hz (the transit between the two areas is 400MW from left to right) when using classical AVRs only [11]. The active power and the terminal voltage at generator 2 are shown in Fig. 8 in case of a step of the terminal voltage set point. Two cases are considered :

(i) no PSS on the machines (solid line);

(ii) a coordinated AVR/PSS in each area, on generators 2 and 12 (dotted line). The other machines are equipped with the AVRs of [11].

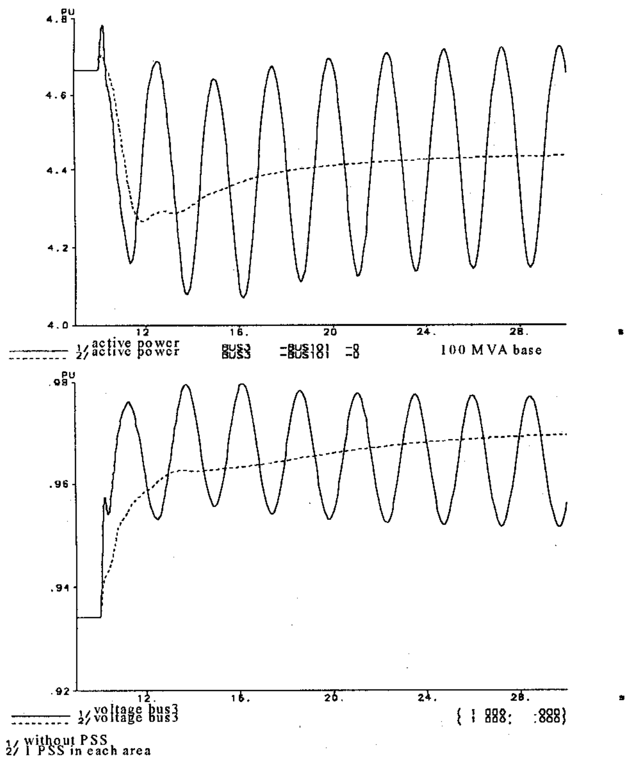

Fig.8 Step on V_{sc}

Clearly, putting a coordinated AVR/PSS in each area is very efficient for damping local and inter-area oscillations. The low mode is due to the speed controller.

V. CONCLUDING REMARKS

The approximations used in Section III bridge the gap between the DFLR structure (which is a state feedback controller including an integrator on the regulation error) and the standard AVR+PSS structure IEEE ST1A + PSS1A. This makes it possible to optimize the parameter values of the latter structure using the methods of modern control theory. In this paper, the desensitivity method is used in order to obtain a coordinated AVR+PSS having a good robustness against parametric uncertainties (variations of the external reactance, etc.). This robustness was extensively studied in the "single machine-infinite bus" case in [9].

Although the AVR+PSS has been designed using the "single machine-infinite bus" model, the simulation results in Section IV.B prove that it is also efficient for damping the local and inter-area oscillations of a multi-machine system. A reason for this is that when the external reactance X of the infinite bus increases, the frequency of the oscillating mode decreases. As the matter of fact, for X=0.2, $f \cong 1$ Hz, whereas for X=1, $f \cong 0.3$ Hz. Hence, when making the controller robust against large variations of X (using desensitivity), one makes it more efficient for damping low-frequency inter-area oscillations. Additional studies based on a network having a structure similar to that of Fig.7 have shown that the AVR+PSS proposed here is still efficient for damping inter-area oscillations at roughly 0.25 Hz, provided that each area is equipped with at least one such an AVR+PSS.

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BIOGRAPHIES

Henri Bourlès received his Engineering Degree from École Centrale de Paris in 1977, his Ph.D. from Institut National Polytechnique de Grenoble in 1982, and his "Habilitation" from Université Paris XI in 1992. Since 1986, he has been working at the EDF Research Center, currently as Senior Research Engineer.

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Discussion

Z. Yao and V.Rajagopalan (Chaire de recherche industrielle Hydro-Québec-CRSNG, Université du Québec, Trois-Rivières, Québec, G9A 5H7, Canada) **:**

The authors have presented an interesting new method of analysis and design of robust coordinated AVR/PSS for excitation control of generators. Such a robust coordinated AVR/PSS is insensitive to operating conditions of the generators and impedance in a "single-machine-infinite-bus" system.

However, a PSS usually is not very sensitive to operating conditions and impedance value in comparison with **network structure** and **controllers** used by other components, such as generators and FACTS devices in power systems. That means, the performance of a PSS depends much on interactions between controllers of different components rather than on the equivalent impedance and operating conditions of generators. Therefore, it would be much more interesting to check the sensitivity of a PSS to this kind of interactions.

Furthermore, one of the main problems of PSS lies in the fact that by a PSS, it is very difficult (if not impossible) to get satisfactory damping to oscillations in a large band of frequency, for instance, the conventional Four Loop Regulator can improve low frequency oscillation but it degraded torsional oscillation in some cases. So, it would be necessary to show that this new PSS could improve this problem.

Finally, we would like to indicate that a comparison between a conventional PSS and the new one proposed in the paper would be more convincing than that presented in Fig. 8 between an AVR without PSS and the new PSS.

Henri Bourlès (Electricité de France, Direction des Etudes et Recherches, 92141 Clamart Cedex, France):
First of all, I would like to thank MM. Yao and Rajagopalan for their interest in our paper and for their pertinent questions.

1. I think that there is a strong relationship between the sensitivity of a PSS to the network structure and its sensitivity to the impedance value. Changes in the network structure can indeed be (roughly) represented by changes in the impedance value (case of line outages, for example). Therefore, to some extent, the more a PSS is robust to the impedance value, the more it is robust to the network structure. This is confirmed by the behavior of the French power system, where every big generator is equipped with the "Four Loop Regulator" (FLR) which is very robust to the impedance value. Due to this robustness, the French power system is very robust to changes in the network structure.

2. The problem of interactions with other components (especially, other generators) is quite different. For example, in case of a generator tripping, the other generators (equipped with PSS) must not be too much disturbed. This means that those PSS must not be too sensitive to variations of the network frequency. In other words, the action of the PSS must not be too strong. This requirement is contradictory with the robustness to the impedance value (for which a strong stabilization effect is needed). Therefore, a good compromize has to be found. This is why the FLR, currently implemented on the French generators, will be replaced by the "Desensitized Four Loop Regulator" (DFLR), proposed in ref. [7], [9] and in the present paper. This controller is indeed much less sensitive than the FLR to variations of the network frequency (although its robustness to the impedance value is still very satisfactory): the above-mentioned compromize is better. Many simulations have shown that by decreasing the sensitivity to the network frequency, the interaction with other generators also decreases.

3. It is true that several years ago, the FLR had a bad effect on the torsional oscillation. This problem has been solved using a filter. The filter proposed in ref. [10] is particularly suitable.

As is mentioned in the Concluding Remarks, the frequency of the oscillating mode of the single machine–infinite bus system is very dependent on the impedance value. Therefore, the more a PSS is robust to this value, the larger is the band of frequency on which it is efficient. Hence, this band is pretty large in the case of the PSS we are proposing, and this is why it is efficient for damping local oscillations and inter-area ones as well. But, as was said above, some additional filtering may be useful.

4. I fully agree that a comparison with a conventional PSS is very important, and such a comparison has been extensively made in ref. [9].

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