According to Remark 1, and considering (16), we only have to check (21) for the value $b_1 = 7.5$. It is readily verified that (21) is satisfied for $b_1 = 7.5$, concluding that the system under test is stable.

III. Sufficient Condition for Instability of n-D Systems

Let the characteristic polynomial of a discrete n-D system be (12) as in the previous section. The following set of sufficient conditions for instability were presented in [6] and are extensions of a result for $n = 1$ by Thoma and by Cohn (cf. [1]). Equation (13) is violated if, for some $j \in \{1, \cdots, m\}$,

$$|a_j| > \sum_{\substack{r=0 \\ r\neq j}}^{m} |a_r|, \qquad j \in \{1, \cdots, m\}. \tag{22}$$

If none of the m conditions in (22) is satisfied, we form the polynomials $P_i(z)$, $i = 1, \cdots, n$ as in (15) under the constraint (16). Any of the conditions (22) can now be checked with the coefficients of any of the polynomials $P_i(z)$. To save computations, the best chances are with the condition in (22) for which (22) was originally closest to be satisfied. If any of the conditions (22) is satisfied for one of the $P_i(z)$'s, we conclude that the original $Q(z)$ is unstable. Note that the two remarks in the previous section are applicable here too.

Remark 3: The above sufficient condition for instability is also applicable to one-dimensional systems ($n = 1$). However, since for 1-D systems stability is defined by $Q(z) \neq 0$ in $|z| \geqq 1$ whereas for n-D systems ($n > 1$) it is customarily defined by $Q(z) \neq 0$ in $\bigcap_{i=1}^{n} |z_i| \leqq 1$, we must assume for $n = 1$ that $Q(z)$ is the reciprocal polynomial.

The following two examples will further clarify the proposed method.

Example 2: Let the characteristic polynomial of a 1-D discrete system be

$$Q(z) = z^4 + 7z^3 + 2z^2 + 2z + 3 \tag{23}$$

and test whether

$$Q(z) \neq 0, \qquad |z| \leqq 1$$

neither the sufficient condition for stability (4) nor those for instability (22) are satisfied. However, for $j = 1$ (the coefficient of z^3), (22) is "almost" satisfied. Hence, we try (22) with

$$P_1(z) = (z-b)Q(z) = z^5 + z^4(7-b) + z^3(2-7b) + z^2(2-2b) + z(3-2b) - 3b \tag{24}$$

where

$$|b| > 1$$

and with a_j, the coefficient of z^3. This renders

$$|2-7b| > 1 + |7-b| + |2-2b| + |3-2b| + |3b| \tag{25}$$

which is readily seen to be satisfied for $b = 7$, concluding that the system under test is unstable.

Example 3: Test whether

$$Q(z_1, z_2) = z_1^3 z_2^2 + 2z_1^2 z_2 + 2z_1^2 + 7.5 z_1 z_2 + z_1 + z_2 + 1 \neq 0$$

$$\text{in } \bigcap_{i=1}^{2} |z_i| \leqq 1. \tag{26}$$

Using (15), we obtain

$$P_1(z_1, z_2) = (z_1 - b_1) Q(z_1, z_2)$$
$$= z_1^4 z_2^2 + 2z_1^3 z_2 + 2z_1^3 - b_1 z_1^3 z_2^2 + z_1^2 z_2 (7.5 - 2b_1) + z_1^2(1-2b_1) + z_1 z_2 (1 - 7.5b_1) + z_1(1-b_1) - b_1 z_2 - b_1 \neq 0$$

$$\text{in } \bigcap_{i=1}^{2} |z_i| \leqq 1. \tag{27}$$

We will conclude that (27) is violated (and, therefore, (26) is also violated) if there exists a real $b_1 \ni |b_1| > 1$ such that

$$|1 - 7.5b_1| > 5 + 3|b_1| + |7.5 - 2b_1| + |1 - 2b_1| + |1 - b_1|. \tag{28}$$

According to Remark 1 the only value to be checked is $b_1 = 7.5/2 = 3.75$, for which it is readily verified that (28) is satisfied. Hence, the system under test is unstable.

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Modeling and Control of a 180 MW Power System

J. VAN AMERONGEN, H. W. M. BARENDS, P. J. BUYS, AND G. HONDERD

Abstract—**This note describes the modeling of the power and voltage control loop of a thermal power plant of 180 MW. The modeling is based upon full-scale measurements at the Flevo power plant of the PGEM. A relatively simple ninth-order mathematical model of one unit for several working points has been developed. Based on this model the existing controller structure has been analyzed and an improved voltage control system designed. The design method is based on a state-feedback technique and pole placement. By means of computer simulations in an extended nonlinear model of this unit, including the grid, the existing and the newly developed control algorithms are compared.**

Field tests have been carried out to verify the results of the designed control algorithms.

I. Introduction

In the last decade much effort has been spent in stabilizing the combined voltage-power control systems of synchronous generators. The use of accelerating power in a power system stabilizer (PSS) has, in particular, turned out to have attractive properties; to obtain this signal, several suggestions have been made [1]–[3]. Multimachine power systems have also been given attention [4]. In these references the reconstruction of the accelerating power signal, the tuning of the stabilizer, and the sensitivity to parameter changes in different operating points have also been discussed.

This note does not claim a new approach; in connection with some problems with the instrumented, conventional voltage controller in the Flevo power station via a systematic analysis-simulation-synthesis ap-

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proach, the implementation of the most simple solution is sought. Because of the pole–zero model used, questions on the stability margin and sensitivity to parameter variations can easily be detected. Some rather practical technical points concerning the identification using a dedicated CAD facility as well as the implementation of an observer circuit are also dealt with.

The project started in 1981 as part of a coordinated research effort between the regional electricity board PGEM (Provinciale Gelderse Energie Maatschappij) and the Control Laboratory of the Delft University of Technology. The primary goal concerned studying the dynamic behavior with regard to small disturbances in different operating points of the two installed 180 MW thermal power plants in the Flevo power station in Lelystad. In the past, a tendency toward oscillating the exchange of power between the two 180 MW units has been observed.

The main purpose of the research project was to get better insight into the phenomena leading to this marginally stable behavior and to formulate a better control strategy, especially with respect to the voltage-control loop. The first part of this research includes the development of a relatively simple control model of one generator connected to an infinitely strong grid. This assumption leads to a simple model. The plant in situ shows quite a different behavior. Therefore, the second step concerns the verification and parameterization of this model for several operating points by full-scale measurements. In this phase the effect of parameter variation in the voltage control loop is also analyzed. In the last and crucial part, a more stable control structure for the combined power and voltage generator system has been designed. The newly developed control structure can be described as a modified system-stabilizer network, where the accelerating power signal is used to increase the damping of the system. In the upcoming sections attention is paid to the modeling and simulation aspects of the system as well as to the principal ideas behind the design of the control structure, including some results. Because of the situation in the power station, the original one-unit model is extended to a two-generator model and the effect of the newly developed voltage control on the stability with respect to load variations and voltage fluctuations is shown. The results are verified in a field test.

II. Modeling of the Power-Voltage-Generating System

A block-oriented third-order model of the generator connected to an infinitely strong grid follows with a few assumptions, from the linearization of the Park equations for a three-phase synchronous machine in a given operating point.

In Fig. 1 this third-order generator model is extended with the speed-control loop, including the approximated steam valve transfer and turbine transfer functions and with the voltage regulator. The parameterization of this model is realized by full-scale measurements in the Flevo power station. These measurements are carried out by applying the following stepwise disturbances to the unit:

2.5 and 5 percent stepwise variations in the set point of the steam valve, i.e., the power set point, while the voltage-control loop is kept in the manual mode (feedback-loop open).

2.5 and 5 percent stepwise variations in the voltage set point while the steam valve is maintained at a constant value (power-feedback loop open).

These measurements are done at various operating points; the results on two operating points, namely an inductive point 150 MW/60 MVAR and a capacitive point 100 MW/ − 10 MVAR, are shown in this note. At the same time two values of the gain in the voltage-control loop are used and a separate set of measurements is performed to check the influence of the instrumented current feedback on the stability.

The results of the modeling and identification lead to the following conclusions.

1) The ninth-order model of the unit reasonably resembles the measured behavior.

2) An elementary analysis of the data leads to the conclusion that the contribution of the primary control loop to the dynamic behavior of the generator system can be neglected.

3) For the different operating points and taking into account the observed variation in the values of K_i's, the s-plane configuration of the present-day system shows quite an insensitive picture with the following

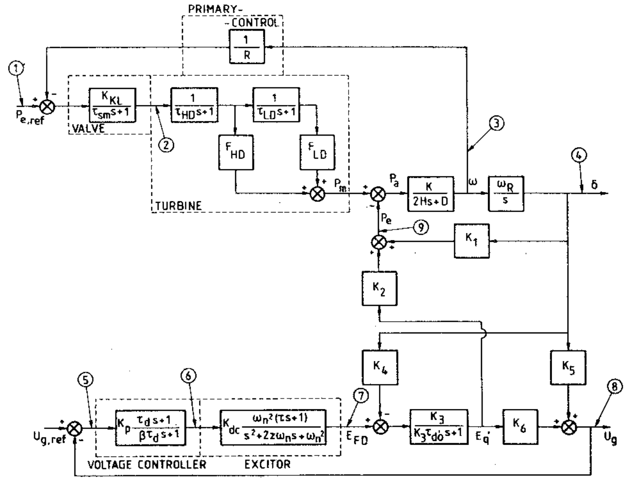

Fig. 1. Block diagram of unit including primary and voltage controller.

poles:

$$p_{1,2} \approx -2+9j \qquad p_7 \approx -13$$

$$p_{3,4} \approx -1.7+2j \qquad p_8 \approx -4.5$$

$$p_5 \approx -0.5 \qquad p_9 \approx -0.1$$

$$p_6 \approx -15$$

III. Voltage-Controller Design

The main aim of the design is to transform the marginally stable poles in $-2 + j.9$ into a more stable position, defined by $-9 + j.9$. In earlier work it has been reported that a PD controller in the voltage-control loop is unable to perform this transformation [10]. A well-known approach to providing a system with a desired pole location is the application of state feedback [8]. Feedback of any of the states of the voltage-control loop does not solve the problem. In terms of a root-locus technique this feedback makes complex zeros appear near the complex poles in $-2 + 9j$. From a general study of possible state-feedback structures to the voltage-set point, it follows that the generator can be stabilized by the use of the relatively fast excitation system, by feeding back the accelerating signal P_a (Fig. 1). The complex zeros are then no longer present. The optimal parameter settings for the P_a feedback signal are analyzed by means of another CAD program developed at the Control Laboratory in Delft [9]. For the 100 MW/60 MVAR operating point: the root locus equation for variations in the gain K_0 of this feedback signal is

$$\frac{s(s+2,5)(s+0,65)}{(s^2+4s+85)(s^2+3,\ 4s+7)(s+0,5)(s+15)} = -\frac{1}{aK_0}.$$

The complex zeros are no longer present in the equation, which considerably simplifies the design of a compensation network. The design procedure concerns the choice of a stabilizing network STB (s), as indicated in the block diagram of Fig. 2. According to a method developed by Fleming *et al.* [12] the general form of STB (s) is chosen

$$\text{STB } (s) = K_0 \frac{as^2+bs+1}{(0{,}05s+1)^2}.$$

With the restrictions that there should be a complex pole pair in $-9 + j9$ and all the other poles should be on or below the time of constant relative damping $z = 0, 7$, we find

$$\text{STB } (s) = K_0 \frac{0{,}007s^2+0{,}17s+1}{(1+0{,}05s)^2} \text{ with } K_0 = 0{,}1.$$

Fig. 3 sketches the root locus for variation of K_0. For $K = 0, 1$ there are two poles in $-9 + j.9$. The other poles are on or lower than the line of

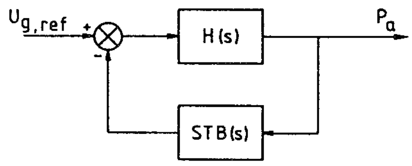

Fig. 2. Block diagram of generator with P_a feedback.

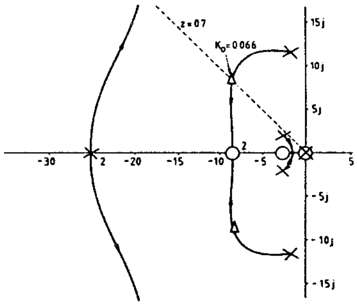

Fig. 3. Root locus for variation in K_0 of the generator with P_a feedback via STB(s).

constant relative damping $z = 0.7$. Simulation experiments show that the designed system is not very sensitive to the parameters of the compensation network nor to those of the generator system under different operating conditions. The generator is connected firmly to the grid. The fictive impedance from the generator terminal to the infinitely strong grid is 0,13 pu (based on generator MVA rating).

The same compensation as designed for the inductive operating point 100 MW/60 MVAR yields near-optimal results for the capacitive operating point 100 MW/ − 10 MVAR (see Fig. 4). As stated in the Introduction, in the actual plant the P_a-signal is not available. The use of the electrical output power P_e would wrongly affect the stability when steam-flow variations occur (due to the primary and secondary control). The reconstruction of the P_a-signal is obtained via a simple observer scheme where the straight available values of the steam-valve position θ_v and the electrical output P_e are used. To avoid a nonzero value of P_a in the stationary situation, a high-pass filter is added with transfer function

$$H_f(s) = \frac{s}{s+\alpha} \qquad \alpha \text{ approximately tuned: } 0.5-1$$

such that a stationary error in the P_a-signal is rapidly decaying (but without influencing the working frequency range). Fig. 5 gives the observer scheme.

IV. Field Tests

In April 1984 field tests were carried out. Some of the results are shown in Figs. 6 and 7. The implementation test emphasizes both the improvement in stability and the fact that the designed stabilizing control is quite insensitive to parameter variations in different operating points.

V. Conclusions and Suggestions

The following conclusions can be drawn.

The low-order model of the generator system combined with a measurement and identification procedure yields a suitable model for the design of a control structure, if focused on the dynamic steady-state stability of the generator. Despite the variations in the generator constants $K_1, \cdots, K_6$ the pole placement remains reasonably constant.

Conventional controllers in the voltage loop are not capable of essentially increasing the damping of the system.

Application of the feedback of the accelerating power of the generator P_a, to the voltage-control loop, as based on the concept of state feedback and combined with a suitably chosen stabilizing network, improves the system stability considerably.

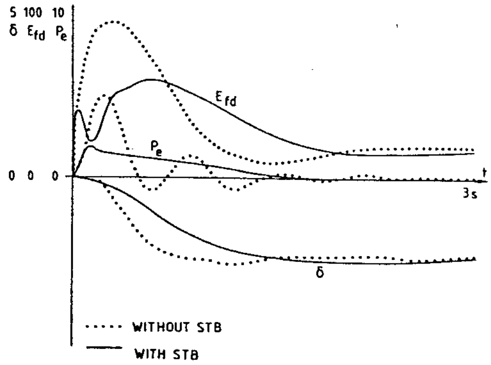

Fig. 4. Simulated responses to a step disturbance of $U_{g,ref}$ with (solid lines) and without (dotted lines) P_a feedback.

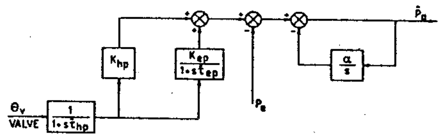

Fig. 5. Simple observer for P_a.

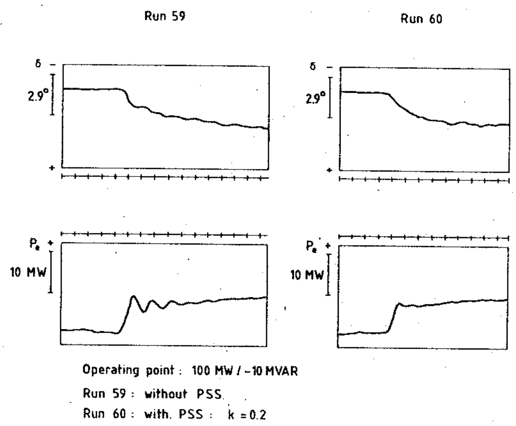

Fig. 6. Field test results for a 5 percent-stepwise variation of $P_{e,ref}$.

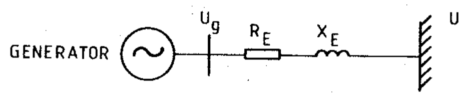

Fig. 7. Electrical strength of bus connection.

The newly designed P_a stabilizing circuit, known in the literature as the power-system stabilizer (PSS), is fairly insensitive to variations in the network configurations under consideration, with respect to the number of generators within the observed power station as well as with the grid.

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Minimax Linear Smoothing for Capacities: The Case of Correlated Signals and Noise

H. VINCENT POOR

Abstract—**Results of an earlier paper giving minimax linear smoothers for the problem of estimating a homogeneous signal field in an additive orthogonal noise field when both have uncertain spectral properties, are extended to the case in which the signal and noise fields are arbitrarily correlated. As before, spectral uncertainty is modeled by assuming that the spectral measures of the signal and noise fields lie in classes of measures generated by two-alternating Choquet capacities. It is demonstrated that this problem admits a general solution in terms of the Huber–Strassen derivative between the capacities that generate the uncertainty sets, and that the least favorable spectra for smoothing in orthogonal noise are also the least favorable marginal spectra for smoothing in correlated noise. The resulting filter is seen to be a zonal filter that also arises as the solution to an analogous problem in (nonparametric) minimax hypothesis testing. These new results extend the applicability of minimax robust smoothing techniques to application involving signal-dependent noise phenomena, such as multipath and clutter, which are usually difficult to model precisely.**

I. Introduction

Consider the observation model

$$Y_z = S_z + N_z, \qquad z \in \mathbb{R}^n \tag{1}$$

where $\{S_z; z \in \mathbb{R}^n\}$ and $\{N_z; z \in \mathbb{R}^n\}$ are second-order, individually and jointly homogeneous, quadratic-mean-continuous random fields representing signal and noise, respectively. Suppose that h is a complex-valued Borel-measurable function on $\mathbb{R}^n$, and let $\hat{S}_z$ denote the linear estimate of S_z based on observing $\{Y_z; z \in \mathbb{R}^n\}$ which has transfer function h. The quadratic-mean estimation error associated with $\hat{S}_z$ is given straightforwardly by

$$E\{|S_z - \hat{S}_z|^2\} = (2\pi)^{-n}\left[\int_{\mathbb{R}^n} dm_S - 2\int_{\mathbb{R}^n} h^*\, dm_{SY} + \int_{\mathbb{R}^n} |h|^2\, dm_Y\right] \tag{2}$$

where m_S and m_Y are the spectral measures on $(\mathbb{R}^n, \mathcal{B}^n)$ associated via Bochner's theorem with $\{S_z; z \in \mathbb{R}^n\}$ and $\{Y_z; z \in \mathbb{R}^n\}$, respectively, and where m_{SY} is the cross spectral measure between $\{S_z; z \in \mathbb{R}^n\}$ and $\{Y_z; z \in \mathbb{R}^n\}$. (The superscript * denotes complex conjugation.) Note that m_{SY} is finite but it may be complex-valued and/or signed.

The expression of (2) can be rewritten straightforwardly as

$$E\{|S_z - \hat{S}_z|^2\} = (2\pi)^{-n}\left[\int_{\mathbb{R}^n} dm_S - \int_{\mathbb{R}^n} \left|\frac{dm_{SY}}{dm_Y}\right|^2 dm_Y + \int_{\mathbb{R}^n} \left|h - \frac{dm_{SY}}{dm_Y}\right|^2 dm_Y\right] \tag{3}$$

where dm_{SY}/dm_Y denotes the Radon–Nikodym derivative of m_{SY} with respect to m_Y. (Note that we always have $m_{SY} \ll m_Y$.) Thus, we see from (3) that the optimum (minimum-mean-quadratic-error) transfer function is given by

$$\hat{h} = \frac{dm_{SY}}{dm_Y}. \tag{4}$$

For the observation model of (1) we have that $m_{SY} = (m_S + m_{SN})$ and $m_Y = (m_S + 2\,\mathrm{Re}\,\{m_{SN}\} + m_N)$, where m_{SN} is the cross spectral measure between $\{S_z; z \in \mathbb{R}^n\}$ and $\{N_z; z \in \mathbb{R}^n\}$ and where m_N is the spectral measure associated with $\{N_z; z \in \mathbb{R}^n\}$. If m_S, m_N, and m_{SN} are known exactly, the quantity in (3) is thus minimized over h by (4). On the other hand, if, as is often the case in practice, these quantities are not known precisely but rather are known only to lie in some uncertainty classes of spectral measures, then a natural alternative to the minimization of (3) as a design criterion is the minimization of the supremum of (3) over these classes. Specifically, if we let $e(h; m)$ denote the quantity (2) for the model (1) where $m = (m_S, m_N, m_{SN})$, then it is of interest to consider the problem

$$\min_{h \in \mathcal{H}} \sup_{m \in \mathfrak{M}} e(h; m) \tag{5}$$

where $\mathcal{H}$ denotes the set of all complex-valued Borel-measurable functions on $(\mathbb{R}^n, \mathcal{B}^n)$ and $\mathfrak{M}$ denotes the class of allowable spectral measures. It is well known that the solutions to problems such as (5) often exhibit robustness properties over the relevant uncertainty classes (see, e.g., [3]).

Aspects of the problem (5) have been considered by Kassam and Lim [2] and by Vastola and the author [5], [6], [8], [10] for the case of orthogonal signal and noise ($m_{SN} = 0$) and by Moustakides and Kassam [4] for the general case. In particular, the general solution to this problem is given in [6] for the case in which the noise and signal fields are known to be orthogonal (i.e., $m_{SN} = 0$) and in which the signal and noise spectral measures are known to lie in uncertainty classes of the form

$$\mathfrak{M}_{v_S} = \{m \in \mathfrak{M} \mid m(B) \le v_S(B),\ \forall\, B \in \mathcal{B}^n, \text{ and } m(\mathbb{R}^n) = v_S(\mathbb{R}^n)\} \tag{6a}$$

$$\mathfrak{M}_{v_N} = \{m \in \mathfrak{M} \mid m(B) \le v_N(B),\ \forall\, B \in \mathcal{B}^n, \text{ and } m(\mathbb{R}^n) = v_N(\mathbb{R}^n)\} \tag{6b}$$

where $\mathfrak{M}$ denotes the class of all (real-valued, positive) measures on $(\mathbb{R}^n, \mathcal{B}^n)$ and where v_S and v_N are *two-alternating capacities* in the sense of Huber and Strassen [1]. It is demonstrated in [6] that the game (5) with $\mathfrak{M} = \mathfrak{M}_{v_S} \times \mathfrak{M}_{v_N} \times \{0\}$ has a saddle-point solution given by (h_0; q_s, q_N, 0), where $h_0 = \pi_0/(1 + \pi_0)$ with $\pi_0 = dv_S/dv_N$, the Radon–Nikodym derivative between v_S and v_N (see [1, p. 257]), and where (q_S, q_N) are elements in $\mathfrak{M}_{v_S} \times \mathfrak{M}_{v_N}$ satisfying $\pi_0 = dq_S/dq_N$

$$q_S(\{\pi_0 \le t\}) = v_S(\{\pi_0 \le t\}), \tag{7a}$$

and

$$q_N(\{\pi_0 > t\}) = v_N(\{\pi_0 > t\}) \tag{7b}$$

for all $t \in [0, \infty]$.

II. Minimax Linear Smoothing for Capacities with Arbitrarily Correlated Signal and Noise

The results of [6] characterize the solutions to (5) for the orthogonal signal and noise case for a very general type of uncertainty set, since

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