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A REALISTIC CONTROL AND STABILISATION STRATEGY FOR DAMPING POWER SYSTEM OSCILLATIONS

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ABSTRACT

This paper describes the application of a realistic proposed control strategy with feedback excitation together with those of conventional power system stabiliser (P.S.S.) and linear optimal control (L.O.C.). Digital simulation results have been obtained using a single machine infinite bus power system dynamic model. The results presented in this paper show that the application of the proposed technique leads to accurate solution, utilising a considerable computer time and less core requirement w.r.t. P.S.S and L.O.C. techniques.

INTRODUCTION

Power systems having long transmission distances often exhibit low frequency power oscillations. The problem known as dynamic instability may also be associated with fast acting high gain excitation systems. To overcome these low frequency oscillations power systems are equipped with supplementary excitation controls which are commonly referred to as power system stabilisers (P.S.S.) [1]. The input to these P.S.S. are normally the frequency, the rotor speed or electrical power output.

Considerable emphasis has also been placed on optimal control of excitation for improvement of power system stability. The excitation control, which is optimal with respect to a given performance index, has been studied by several authors [2-4] and has been shown to provide real advantages in stabilisation and operation of power systems.

Most of these optimisation techniques suffer from doubling the dimension of the system due to the solution of a two-point boundary value problem.

In this paper, a realistic control and stabilization strategy is given and tested to a linearized model of single machine connected to an infinite bus system. The obtained results have been compared with those obtained using optimisation techniques and also with those obtained using conventional power system stabilisers.

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THE CONTROL STRATEGIES

Optimal Linear State Regulator

The linear state regulator control is well documented in the standard texts and is presented here briefly [1].

For the linear system corresponding to the power system model, the control law u (t) which minimises

$$J = 1/2 \int_{t_o}^{t_f} (X^T Q\, X + u^T R\, u)\ dt \tag{1}$$

subject to

$$\dot{X} = Ax + Bu$$

is given by the feedback control law in terms of states as:

$$\overset{*}{u} = -R^{-1}\ B^T K\ X \tag{2}$$

where $$0 = A^T K + KA - KBR^{-1} B^T K + Q \tag{3}$$

For a given A, B and Q matrices, a closed loop solution of Eqn. (3) is possible in terms of eigenvectors of the extended system equations.

The Conventional Power System Stabiliser

Power system stabilizers are presently being used in many power utilities to overcome the negative damping effect introduced in long lines. The transfer function of the stabilizer depends on the type of input.

For an input proportional to the output power of the synchronous machine a transfer function of the following form [6] is used in this paper:

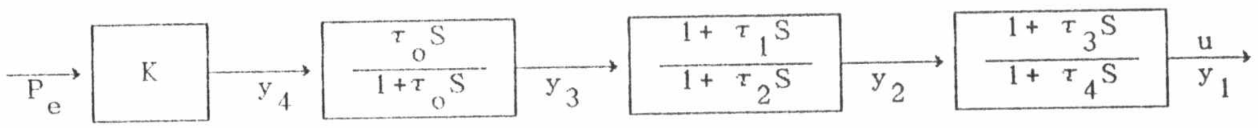

Fig. (1) : Conventional P.S.S.

By choosing the output of the various blocks as $y_1(u)$, y_2, y_3 and y_4, it is a simple matter to show that the three state equations arising out of P.S.S. are:

$$\dot{Z}_1 = \frac{K\,\tau_1}{\tau_2}(1 - \tau_3/\tau_4)\,P_e - \frac{1}{\tau_4} Z_1 + \frac{1}{\tau_2}\left[1 - \tau_3/\tau_4\right] Z_2 + \frac{\tau_1}{\tau_2\,\tau_o}\left(1 - \frac{\tau_3}{\tau_4}\right) Z_3 \quad (4)$$

$$\dot{Z}_2 = K\left(1 - \frac{\tau_1}{\tau_2}\right) P_e - \frac{1}{\tau_2} Z_2 + \frac{1}{\tau_o}\left(1 - \frac{\tau_1}{\tau_2}\right) Z_3 \quad (5)$$

$$\dot{Z}_3 = - KP_e - \frac{1}{\tau_o} Z_3 \quad (6)$$

where $y_1 = \frac{1}{\tau_4}(\tau_3\, y_2 + Z_1)$;

$$y_2 = \frac{1}{\tau_2}(\tau_3\, y_2 + Z_1) ;$$

$$y_3 = y_4 + \frac{1}{\tau_o} Z_3$$

The control u in terms of the state variables is

$$u = \frac{K\,\tau_1\,\tau_3}{\tau_2\,\tau_4} P_e + \frac{1}{\tau_4} Z_1 + \frac{\tau_3}{\tau_2\,\tau_4} Z_2 + \frac{\tau_1\,\tau_3}{\tau_o\,\tau_2\,\tau_4} Z_3 \quad (7)$$

The state equations (4) - (6) combined with equations representing the system give an augmented system of equations in the form

$$\dot{X} = A\,X + B\,u$$

where X is (6x1) vector. P_e can be expressed in terms of the original state variables X.

Proposed Control and Stabilisation Strategy

In this section a realistic control design for linear systems is presented. The main idea of this method is to solve the optimisation problem without introducing by means of Lagrange multiplier the equality constraint which characterises the process. The optimisation problem of the dynamical system may be written as:

$$\min_u J = 1/2 \sum_{k=o}^{K} (X^T_{k+1} Q\, X_{k+1} + u_k^T R\, u_k) \quad (8)$$

subject to

$$X_{k+1} = A \; x_k + B \; u_k$$

with

$$Q \geq 0 \; ; \quad R > 0$$

The solution is now being made by a decomposition-coordination technique [9].

Decomposition replaces the global problem by a number of sub-problems which can be solved simultaneously and a coordination to push the solution to the optimal one. The global criterion may be now decomposed as:

$$J = J_k + \bar{J}_k \tag{9}$$

J_k is the local criterion which is chosen arbitrarily

Let

$$J_k = 1/2 \left[X^T_{k+p} \; Q \; X_k + u^T_k \; R \; u_k \right] \tag{10}$$

$$\bar{J}_k = 1/2 \left[\sum_{\ell \neq k} X^T_{\ell+1} \; Q \; X_{\ell+1} + u^T_\ell \; R \; u_\ell \right] -1/2 \; X^T_{k+p} \; Q \; K_k \; -1/2 \; u^T_k \; R \; u_k \tag{11}$$

Applying stationarity condition for eqn. (9) we obtain

$$\frac{\partial J_k}{\partial u_k} + \frac{\partial \bar{J}_k}{\partial u_k} = 0 \qquad \forall \; k = 1, 2, \ldots, K \tag{12}$$

Assume that the second term is constant, $\rho_k = (\partial \bar{J}_k) / (\partial u_k)$, and has the same dimension as u_k.

The local subproblems may be thought as

$$\underset{u_k}{\text{Min}} \; C_k = J_k + \rho^T_k \; u_k \tag{13}$$

subject to $X_{k+1} = Ax'_k + Bu_k$

The solution in this case is given by

$$u_k = -1/2 \; R^{-1} \; B^T A^{TP} \; Q \; X_k + 1/2 \; R^{-1} \; \rho_k = \Gamma \; X_k + \Lambda \; \rho_k \tag{14}$$

$$\Gamma = -1/2 \; R^{-1} \; B^T \; A^{TP} \; Q \quad , \quad \Lambda = -1/2 \; R^{-1}$$

$$\rho_k = \frac{\partial \bar{J}_k}{\partial u_k} = B^T \; W_k - \delta \; k \tag{15}$$

with $$W_{k-1} = Q X_k + \Gamma^T R u_k + (A + B\Gamma)^T W_k \tag{16}$$

; $$W_K = Q X_{K+1}$$

and
$$\delta_k = 1/2 \, B^T (A + B\Gamma)^{T(P)} Q X_k$$

It is found that the suitable choice of local criterion, as given in (10) achieves the stable operation of the system. This choice leads to stabilizing control laws given in (14). This control has great influence on the system state vector. The influence matrix $(\partial X_{k+p})/(\partial u_k)$ is considered as a measure for this effect. This inturn depends on the value of p.

For this reason, one can also use the proposed method [9] to find an exact value of p. It becomes necessary to build a global criterion H(p) weighting the input-output couples. H(p) may be given as

$$H(p) = \sum_{i=1}^{m} n_i \mid \dot{X}_{ip} \mid \tag{17}$$

where $\{ \dot{X}_{ik} \}$ represents the discrete slope function of $i^{\underline{th}}$ step response $\{X_{ik}\}$. The positive weighting coefficient n_i is selected such that $n_i = Q_i$. The integer p is chosen at the maximum of the slope criterion H.

$$p = \operatorname{Arg}\max_{n} H(n) \tag{18}$$

It has been found that the obtained value of p corresponds to that obtained by minimising the spectral radius δ (p) of the resulting closed loop matrix

$$\tilde{A}_p = A + B\Gamma_p$$

The spectral radius δ (p) of the matrix $A_p = \text{Max} \, \| \lambda_{ip} \|$, $i = 1,N$

where N is the number of the system eigenvalues.

and $$\| \lambda_{ip} \| = \sqrt{(\text{Real part})^2 + (\text{Imag part})^2}$$

POWER SYSTEM MODEL

The model under investigation represents a $3^{\underline{rd}}$ order model of a single machine connected to an infinite bus systems. This model is represented in the following state variable form:

$$\dot{X}_1 = X_2 \tag{19}$$

$$\dot{X}_2 = B_1 - A_1 X_2 - A_2 \sin X_1 \cdot X_3 - B_2 \sin 2 X_1 \tag{20}$$

$$\dot{X}_3 = u_1 - C_1 X_3 + C_2 \cos X_1 \tag{21}$$

X_1 = power angle δ : X_2 = rotor speed S

X_3 = field flux linkage ψ_f

Details of this model are found in [7].

The system, initially in steady state, was disturbed by a step change in power input pi, which was brought down to 0.68 p.u. from 0.725 p.u., and was again brought back to the original magnitude after a time lapse of 0.35 sec.

The resulting initial conditions of the state variables were

$X_1(o) = 0.7347$, $X_2(o) = 0.2151$, $X_3(o) = 7.7443$

The non-linear model given in eqn. (19-21) is linearized about the state values of system variables

$X_{1_F} = 0.7461$, $X_{2_F} = 0.0$, $X_{3_F} = 7.7438$

SIMULATION RESULTS

The optimization problem was solved by the three presented techniques for a final time T = 2.0 sec. The P.S.S. parameters were selected such that the transient response of the system in terms of over-shoot and settling time was optimised.

Figs. (2-4) display the transient response of the machine with constant excitation and with control. With no control, the system is dynamically stable but with a low decay rate. From torque angle and rotor speed variation responses, it is observed that proposed strategy gives the best response following in descending order by the linear regulator-control and P.S.S.

Figs. (2-4) also show that the proposed technique drives the exciter to the ceiling more rapidly than other two stabilisers, and so it tries to bring frequency deviation and acceleration of the machine to zero in minimum time. The core requirements and computing time required for the proposed technique are much smaller w.r.t. other techniques.

An application of the proposed method given in [9] for the purpose of determination of the optimal value of p is carried out. From Fig. (5) it is found that this value of p equals 20. This value also found to be coincident with that obtained by minimising the spectral radius of the closed loop system of the matrix

$\tilde{A}$ eigenvalues. This ensures that the proposed control action not only minimises the performance index but also has an efficient stabilizing effect.

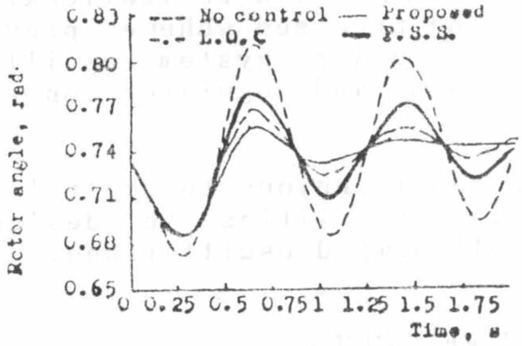

Fig. 2. Transient response of rotor angle.

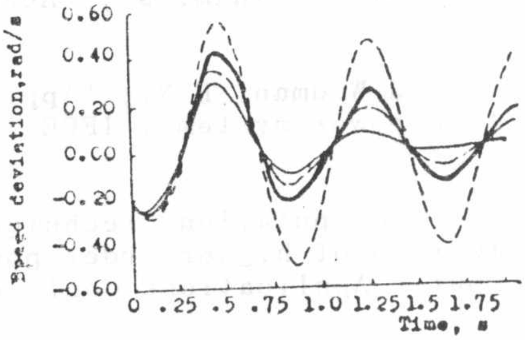

Fig. 3. Transient response of speed deviation.

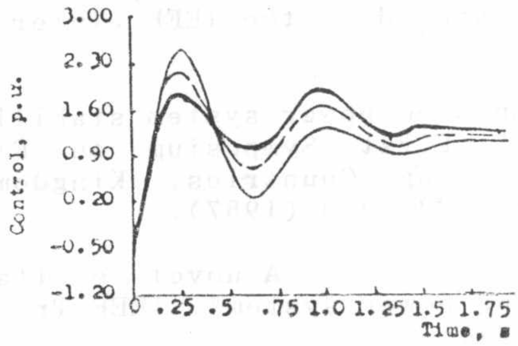

Fig. 4. Variation of control input with time.

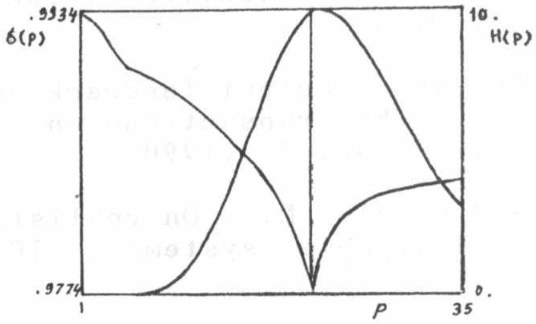

Fig. 5. Variation of H(P) and σ (P) with P.

CONCLUSIONS

Results obtained with the proposed optimal excitation control strategy are compared with those of with conventional P.S.S. and L.O.C. It is observed that the proposed scheme provides better damping characteristics, for power system oscillations. The scheme is superior to both P.S.S. and regulator control in terms of transients.

The application of the proposed technique to control synchronous machines shows its extensive possibilities to design efficient control laws resulting in well damped oscillations.

REFERENCES

1- Yu, Y.N., "Electric Power System Dynamics", Academic press, (1983).

2- Yu, Y.N.; Vongusriya, K.; and Wedman, L.N.; "Application of an optimal control theory to a power system", IEEE Trans., PAS-89 pp. 55-62, (1970).

3- Wedman, L.N.; and Yu, Y.N., "Computation techniques for the stabilization and optimization of higher order power systems", IEEE, Power Industry Computer Applications Conference Record, pp. 324-343, (1969).

4- Iyer, S.N., and Cory, B.J., "Optimisation of turbo-generator transient performance by differential dynamic programming", Paper 71 Tp 72-PWR, Presented at the IEEE Winter Power Meeting, New York (1971).

5- Rahim, A.H.M.A. "An improved power system stabilizer for damping power oscillations", First Symposium on Electric Power Systems in Fast Developping Countries, Kingdom of Saudi Arabia, March 21-24, pp. 337-340 (1987).

6- Doraiswami, R. and Castro, J.C., "A novel excitating control design for multi-machine power system", IEEE Trans. PAS, Vol. 103, pp. 1052-1058 (1984).

7- Mukhopadhyay, B.K., and Malik, O.P., "Optimal control of synchronous-machine by quasilinearisation techniques", Proc. IEEE, Vol. 119, No. 1, (1972).

8- Huag, PEI-HWA, Hsu, Yhan-Yhi, "Output feedback controller for a synchronous generator", IEEE Transactions on aerospace and electronic systems, Vol. 26, No. 2, (1990).

9- Mariton, M., Duc, J. and Drouin, M., "On realistic hierachical control design for multi-variable systems", IFAC, Budapest, (1984).