A QUASI-OPTIMAL STABILIZING CONTROL OF POWER SYSTEMS WITH DUAL-EXCITED MACHINES

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ABSTRACT

A quasi-optimum feedback control strategy for stabilizing doubly-excited machines in a power system is proposed. The control strategy depends only on local information pertaining to each machine in the system. The strategy was tested via simulation on a single machine as well as a multimachine system. It has been observed that the addition of the quasi-optimal control on the quadrature axis field winding provides a much better transient response compared to when it is applied to the direct axis field winding only.

1. INTRODUCTION

Numerous studies and field tests indicate that fast acting excitation systems offer the best opportunity to increase system damping through the use of auxiliary signals into the voltage regulator. A number of stabilizing control strategies including some optimal and suboptimal ones have been reported in the literature [1-4]. Most modern power systems are equipped with supplementary excitation control devices, commonly referred to as power system stabilizers (PSS). The input to the PSS's normally are speed deviation, accelerating power, etc.

The effect of an additional field winding on the quadrature axis of a synchronous machine is under investigation for some time [5-6]. It has been reported that the transient performance of a power system can be further improved through additional signals applied to the quadrature axis field winding [7]. The authors have investigated the small signal stability problem with dual excited machines in the system through multilevel control strategies using linear optimal control (LOC) theory [8]. It has been observed that with additional stabilizing control in the quadrature axis field winding, the transient response is much superior compared to that having only one field control.

The difficulties in implementing LOC to real systems are well known. The controller requires too many measurements and off-line computations are involved. In this paper, an optimum feedback control strategy based on minimum time formulation is presented. The controls are derived retaining the original system nonlinearities. Also, the strategy does not require any off-line computations. The control strategy has been tested on a single machine infinite bus system as well as on a simple multimachine system.

2. SYSTEM MODEL

A power system is comprised of generators, transformers, transmission lines, loads, etc. The transformers can be modeled with the generators or the transmission lines depending on their location. For simplicity, loads are often represented by constant impedances. For transient stability studies, the dynamics of the governor system are generally not included. The generator voltage, current and fluxes are expressed through Park's variables. These and each generator swing equations are given in Appendix A. The excitation system may require reasonable details and various standard representations are available. To keep the analysis simple, the exciters on both the direct and quadrature axes are represented by the following equations:

$$E_{fd} = \frac{K_{ed}}{1+T_{ed}p}(v_r - v_t + u_{ed})$$

$$E_{fq} = \frac{K_{eq}}{1+T_{eq}p}u_{eq} \qquad (1)$$

Where E_{fd} and E_{fq} are the direct and quadrature axes field voltages referred to the stator side, K_{ed}, K_{eq}, T_{ed} and T_{eq} are the respective gains and time constants of the exciters, u_{ed} and u_{eq} are the auxiliary signals, v_r and v_t are the reference and actual terminal voltage of the machine respectively.

The dynamic equations of all the generating units and their excitation systems can be expressed in the form

$$\dot{X} = F[X,Y,U] \qquad (2)$$

where X is a vector of the state variables chosen, Y includes variables like power, current, etc. (not included in X) and U is a vector containing the auxiliary signals (u_{ed}, u_{eq}) of all the machines in the system. The power flow along the system and transmission interconnection relationship are expressed as

$$G[X,Y]=0 \qquad (3)$$

3. CONTROL STRATEGY

Following a disturbance in a power system, the system states and other variables namely X and Y will be perturbed from their nominal

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values. Any control action should try to bring the variables back to a stable equilibrium point, original or a new one, depending on the nature of the disturbance, with minimum excursion of state and control variables and in reasonable time. In transient stability studies where the disturbance is large, emphasis should be on returning the variables like rotor angle and speed to their stable limit as quickly as possible. The control problem then can be stated as:

Given a system which is represented by equations (2) and (3), find an admissible control from the sets

$$|u_{edk}| \le K_{dk} \qquad k = 1,2,..n$$
$$|u_{eqk}| \le K_{qk} \qquad k = 1,2,..n \tag{4}$$

so as to bring the system to a stable equilibrium point in minimum time. Here n is the number of generators in the system. The cost index can be written as:

$$J = \int_{t_0}^{t_f} dt \tag{5}$$

Normally, the field voltages E_{fd} and E_{fq} are limited by their ceiling voltages. The limits on u_{ed} and u_{eq} given in equation (4) are obtained from these ceiling values, assuming them to be proportional since the time constants are small.

The solution of the optimal control stated above is extremely complicated because of the high order of the system equations (2) and (3). Determination of the controls as a function of X and Y is almost impossible.

In the following, a quasi-optimum feedback strategy for each generator in the system is proposed. The strategy with only one control in the direct axis E_{fd} is given in reference [3]. The procedure is extended to the doubly excited machine as follows:

Differentiation of the swing equation for the k-th machine in the system, as given by equation (A7) in appendix A, results in the following equation:

$$T_m p^3(\delta/\omega_o) = -v_d p i_d - i_d p v_d - v_q p i_q - i_q p v_q \tag{6}$$

The governor action is ignored here. After some manipulation of the voltage, current and flux equations given in appendix A , one can write:

$$p i_d = \frac{(E_{fd} - e_q)}{x'_d T'_{do}} \tag{7}$$

$$p i_q = \frac{(E_{fq} - e_d)}{x'_q T'_{qo}} \tag{8}$$

$$p v_d = x'_q \cdot p i_q + \frac{(E_{fq} - e_d)}{T'_{qo}} \tag{9}$$

$$p v_q = -x'_d \cdot p i_d + \frac{(E_{fd} - e_q)}{T'_{do}} \tag{10}$$

Substituting equations (7) -(10) successively in equation (6) and using the subscript k for the k-th machine, one can write

$$p^3(\delta_k/\omega_o) = L_k(t) + b_{1k}(t)E_{fdk} + b_{2k}(t)E_{fqk} \tag{11}$$

$$= u_k(t) \tag{12}$$

where

$$L_k(t) = \frac{v_d e_q}{T_m x'_d T'_{do}} + \frac{v_q e_d}{T_m x'_q T'_{qo}} + \frac{2 i_d e_d}{T_m T'_{qo}}$$

$$b_{1k}(t) = \frac{v_d}{T_m x'_d T'_{do}}$$

$$b_{2k}(t) = -\frac{v_q}{T_m x'_q T'_{qo}}$$

The time optimal control $u_k(t)$ at any instant of time t is either the maximum value of $u_k(t)$ or its minimum value. The maximum and minimum values of $u_k(t)$ can be obtained by substituting the respective values of E_{fd} and E_{fq} in equation (11) taking care of the signs of b_{1k} and b_{2k}. The control algorithm is given as:

$$u_k(t) = \begin{Bmatrix} u_{k\min} & \text{if} \ \Sigma_1 > 0 \\ u_{k\max} & \text{if} \ \Sigma_2 < 0 \end{Bmatrix} \tag{13}$$

otherwise,

$$u_k(t) = \begin{Bmatrix} u_{k\min} & \text{if} \ \Sigma > 0 \\ u_{k\max} & \text{if} \ \Sigma < 0 \end{Bmatrix} \tag{14}$$

where,

$$\Sigma_1 = \delta/\omega_o - \pi/2\omega_o - n \cdot pn/\alpha + (pn)^3/3\alpha^2$$

$$\Sigma_2 = \Sigma_1 + \pi/2\omega_o$$

$$\Sigma = n - (pn)^2/\beta$$

$$\beta = \begin{Bmatrix} u_{k\min} & \text{if} \ pn > 0 \\ u_{k\max} & \text{if} \ pn < 0 \end{Bmatrix}$$

$$\alpha = \begin{Bmatrix} u_{k\max} & \text{if} \ \Sigma > 0 \\ u_{k\min} & \mathit{otherwise} \end{Bmatrix}$$

$$n = (\omega - \omega_o)/\omega_o$$

A significant reduction in the complexity of the algorithm can be made if it is assumed that the trajectories do not go beyond the hyper-surfaces passing through $\delta = 0$ and $\delta = \pi/2$. This is true in case of controlled machines. The algorithm can then be derived from a second order model and given by equation (14) only. Finally, the stabilizing controls can be expressed as proportional to the switch functions and are expressed as:

$$u_{edk} = k_1 \cdot \Sigma$$
$$u_{eqk} = k_2 \cdot \Sigma \tag{15}$$

where k_1 and k_2 are selected such that the exciters are driven to the ceilings at the onset of a large disturbance.

In deriving the control algorithms given by equations (13) and (14), it is assumed that the reference machine in the system is too large and it is not equipped with a controller. In case the reference is a finite machine, the rotor angle, speed and acceleration of each machine will be replaced by their respective quantities.

4. CASE STUDIES

The single machine infinite bus system shown in Fig.1 was simulated to test the proposed algorithm. The data for the system is given in appendix B. The generator was considered to be supplying power at 90% rated value. The infinite bus voltage and terminal voltages were 1.06 and 1.02 p.u. respectively. For a 10% step increase in the input power, the rotor angle variation of the machine with and without control are shown in Fig.2. The response shown by curve b is with the quasi-optimal control on both the direct and quadrature axes. Fig.3 gives a comparison of the response with the two controls: curve 'a' with control on the direct axis alone, while curve 'b' is with control on both axes. It is clear from the response that dual control is superior over the direct axis field control alone in terms of transient response.

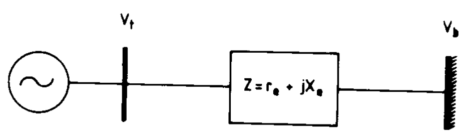

Fig. 1 Single Machine Infinite Bus System.

The 3-machine 9-bus system given in reference [9] was used to test the proposed algorithm on a multi-machine system. The system configuration along with the prefault power flows are given in Fig.4.a balanced 3-ϕ fault on bus 7 for a duration of 0.25 seconds was considered. Generator #1, which is the largest in the system, was taken to be the reference machine.

The transient response of the system was studied considering a) no control in the field windings, b) control on direct axis alone, and c) control on both direct and quadrature axes. Fig.5 shows the rotor angle response of the system when there is no control. For this disturbance, the system is quite oscillatory. The transient response is substantially enhanced with controls on both the direct and quadrature axes as depicted in Fig.6. A comparison of the control strategies - without control, with control on direct axis, and with control on both axes, for machine 2 is given in Fig.7. It is evident that the supplementary control on the quadrature axis field winding is very effective compared to the direct field control alone.

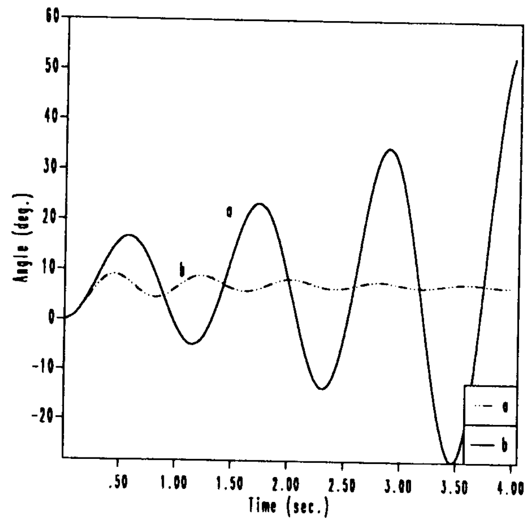

Fig. 2 Angle variation for a 10% input torque step with

a- No control
b- Control on both d-q axes

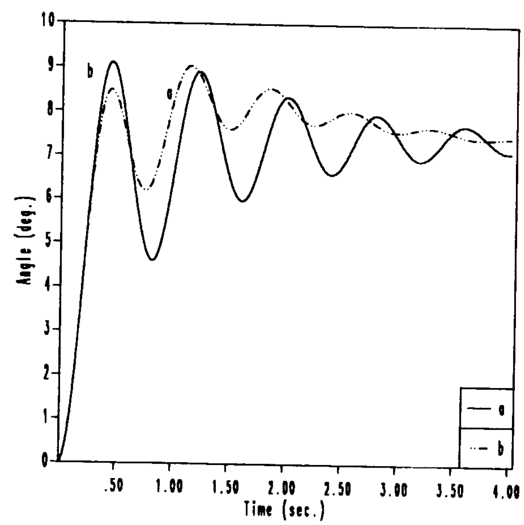

Fig. 3 Angle variation corresponding to Fig. 2

a- Control on d-axis
b- Control on both d and q axis

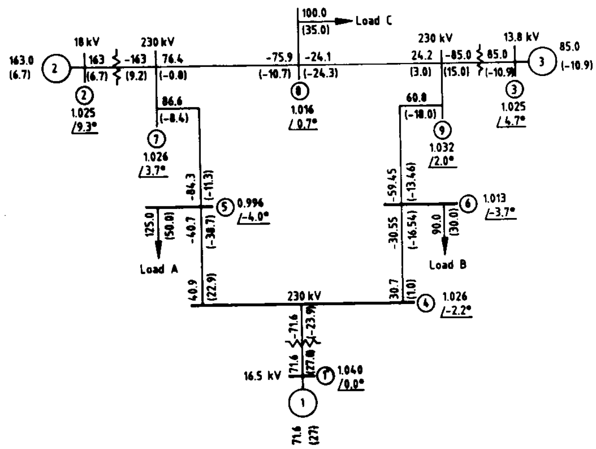

Fig. 4 3-Machine, 9 bus system configuration with prefault power flow. Real and reactive flows are in MW and MVAR (9).

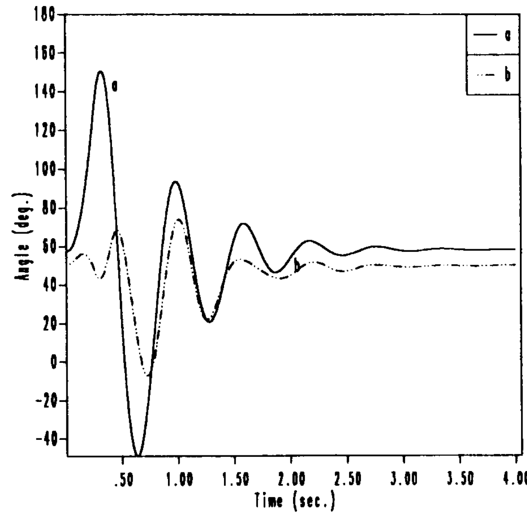

Fig. 6 Rotor angle response corresponding to Fig. 5 with control on both d-q axes

a- Machine 2
b- Machine 3

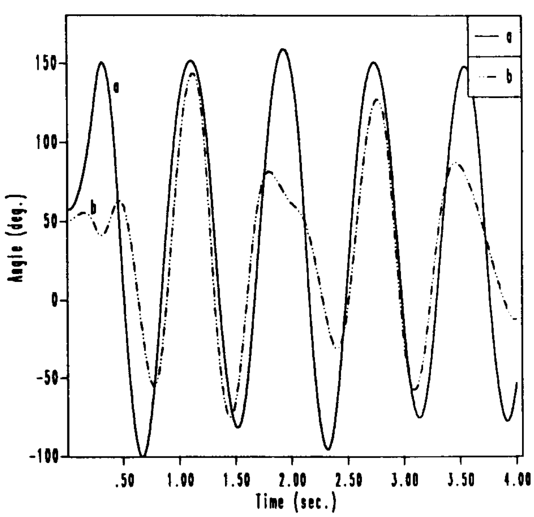

Fig. 5 Rotor angle response for 3-ϕ fault of 0.25 sec. duration on bus 7, without control

a- Machine 2
b- Machine 3

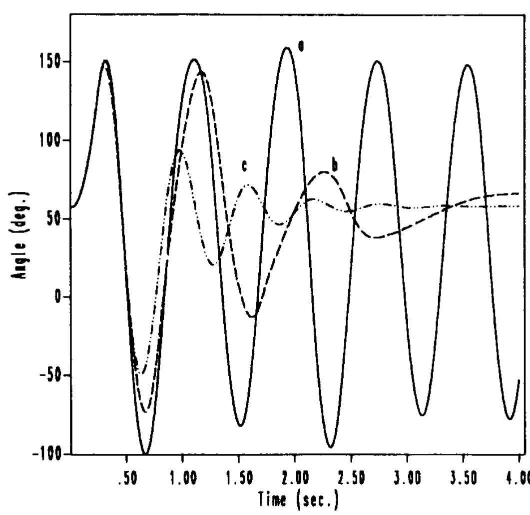

Fig. 7 Rotor angle variation of machine 2 for a 3-ϕ fault of 0.25 sec. duration on bus 7

a- Without control
b- Control is on d-axis only
c- Control is on both d and q-axis

5. CONCLUSIONS

A quasi-optimal feedback control strategy for interconnected power systems with dual-axis excited synchronous generators is proposed. The auxiliary stabilizing controls are constructed directly as a function of the rotor angle, speed etc. of each machine in the system. It has been observed that the transient response is very much improved when a supplementary signal, derived through the proposed strategy, is applied to the quadrature axis field winding. The control strategy is relatively easy to implement because it requires local information pertaining to each generator.

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APPENDIX A

The synchronous generator equations for currents, voltages and fluxes can be written as [10]

$$\begin{aligned}\psi_d &= x_f i_f - x_d i_d\\ \psi_q &= x_g i_g - x_q i_q\\ \psi_f &= x_{ff} i_f - x_f i_d\\ \psi_g &= x_{gg} i_g - x_g i_q\end{aligned} \qquad (A1)$$

$$\begin{aligned}v_d &= -r i_d + x_q i_q + e_d\\ v_q &= -r i_q - x_d i_d + e_q\end{aligned} \qquad (A2)$$

$$\begin{aligned}v_{fd} &= r_f i_f + \frac{1}{\omega_0}\cdot p\psi_f\\ v_{fq} &= r_g i_g + \frac{1}{\omega_0}\cdot p\psi_g\end{aligned} \qquad (A3)$$

The symbols are the same as used in reference [10]. The symbol v_{fq} represents the voltage applied at the quadrature axis field. In writing expressions for v_d and v_q, the transformer voltages $p\psi_d$ and $p\psi_q$ have been neglected and it is assumed that $\omega/\omega_0 \approx 1.0$.

The expressions for e_d and e_q in equation (A2) are

$$\begin{aligned}e_d &= e'_d - (x_q - x'_q) i_q\\ e_q &= e'_q + (x_d - x'_d) i_d\end{aligned} \qquad (A4)$$

where

$$\begin{aligned}pe'_q &= \frac{1}{T'_{do}}[E_{fd} - e'_q - (x_d - x'_d) i_d]\\ pe'_d &= \frac{1}{T'_{qo}}[E_{fq} - e'_d + (x_q - x'_q) i_q]\end{aligned} \qquad (A5)$$

Combining equations (A2) and (A3), one can write

$$\begin{aligned}v_d &= x'_q i_q + e'_d\\ v_q &= -x'_d i_d + e'_q\end{aligned} \qquad (A6)$$

The swing equation for each generator is

$$T_m p^2 \cdot (\delta/\omega_0) = T_i - T_e \qquad (A7)$$

where $T_e = v_d i_d + v_q i_q$

All the above equations are normalized on appropriate bases.

APPENDIX B

Single-machine infinite bus data (in p.u.)

$x_d = 1.0$	$K_{ed} = 50$
$x_q = 0.06$	$K_{eq} = 50$
$x'_d = 0.2$	$T_{ed} = 0.05\,s.$
$x'_q = 0.1$	$T_{eq} = 0.05\,s.$
$T'_{do} = 7.7\,s.$	$r_e = 0.2$
$T'_{qo} = 2.5\,s.$	$x_e = 2.0$