OPTIMUM CONTROL STRATEGIES FOR TRANSIENT AS WELL AS OSCILLATORY INSTABILITY OF POWER SYSTEMS

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Keywords: Transient stability, Dynamic braking, Excitation control.

Abstract

A co-ordinated dynamic braking strategy and excitation control to arrest the first swing instability as well as subsequent oscillations in a power system is proposed. Comparison is made between braking resistor, resistor-reactor and resistor-capacitor strategies with and without excitation control. The control strategies are obtained in terms of system states and other measurable quantities. Assumptions that the reference machine is large and that it is not equipped with dynamic braking facility lead to a simpler control strategy. Excitation strategy can also be significantly simplified by relaxing the constraints on the rotor angle. Computer simulation of a multi-machine system shows that a co-ordinated application of braking resistor-capacitor and excitation strategy controls the transients effectively.

INTRODUCTION

Following a severe disturbance in a power system, it may be first swing unstable if proper control action is not taken sufficiently quickly. In the event the system is able to retain stability, by itself or by a control action, the subsequent oscillations may be quite large and in some cases may even be growing. A power system should be equipped with control devices so that it can maintain large swing (transient) stability and at the same time can preserve a smooth transition to normal operating conditions.

Dynamic braking is one of the effective methods reported to enhance transient stability. Use of dynamic braking resistors were studied in the sixties [1,2]. In the present days, braking resistors are in use in countries like U.S.A., Japan, U.S.S.R, Argentina etc. The Bonneville Power Administration, the Peace River Systems and the Arizona Public Service Comany have good experience with braking resistors [3,4,5]. Various switching sequences of the brakes from the simple velocity signals [3,6,7] to optimum strategies [8,9] have been studied. Usually, the optimum strategy is handicapped in terms of realization. Often the switchings are done on the basis of predetermined, open loop strategies. Aliyu [7] reported a braking strategy which involves switching in a resistor when the machine accelerates and a reactor when it decelerates. The resistor absorbs the excess energy and the reactor reduces the terminal voltage reducing the output power of the machine. A closed loop optimal strategy of switching braking resistor and reactor was given in reference [8]. A recent study showed that a combination of resistor and capacitor eliminates the electromechanical as well as electrical transients in the system better than with just resistor or resistor-reactor strategies [9].

92 WM 152-9 PWRS A paper recommended and approved by the IEEE Power System Engineering Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1992 Winter Meeting, New York, New York, January 26 - 30, 1992. Manuscript submitted January 17, 1990; made available for printing January 13, 1992.

Once the first swing instability of the system is checked, it may continue to remain highly oscillatory. The oscillations may even grow depending on the mode of excitation. Countermeasurs for these types of oscillations are widely reported in the literature [10,11]. Power system stabilizers in the voltage regulator/exciter loop of a machine are almost universally being used in modern systems to overcome the dynamic problem [12,13]. The PSS controls are excellent for slowly varying transients but may not be very effective following a severe disturbance.

This paper proposes simple control laws for both first swing instability and subsequent large perturbation stability enhancement. Resistor, resistor-reactor and resistor-capacitor braking strategies are used for controlling the first swing instability while an optimum exciter control, which takes the system nonlinearities into account, is used for removing subsequent oscillations. Initial results with resistor reactor brake and excitation control were presented earlier [14].

THE CONTROL STRATEGIES

The dynamics of a power system is generally complicated, the extent of complexity depends on the number of generators and associated control elements. Each generator is modelled through a number of differential equations depending on the degree of details required.The transmission systems, transformers and loads are usually reprsented by a set of linear or nonlinear differential equations. Determination of any optimal strategy in such problems is difficult. Finding the control as a function of measurable states, and retaining all the system details and nonlinearities, is almost impossible. This leads to the next best control --suboptimum or quasi-optimum strategies. This paper gives two control strategies for each machine in the system -- one for transient instability and the other for relatively smaller perturbation oscillations. A strategy for dynamic braking resistor, reactor or capacitor is given for the transient problem. An optimum excitation strategy is designed for controlling the subsequent oscillations following a large disturbance.

The Dynamic Braking Strategy

The electromechanical swing equations of the i-th synchronous generator in a multimachine power system can be written as

$$M_i p^2 \delta_i + D_i p \delta_i = P_{mi} - P_{ei}(t) - P_{bi}(t) \qquad (1)$$

where M_i, D_i, P_{mi}, P_{ei}, P_{bi} are the inertia and damping constants, input power, electrical output power of the machine (less power loss in the brakes) and power absorbed in the braking resistor respectively. δ is the rotor angle of the generator with respect to the synchronously rotating mmf and p is the derivative operator d/dt. The location of the braking devices is shown in Figure 1.

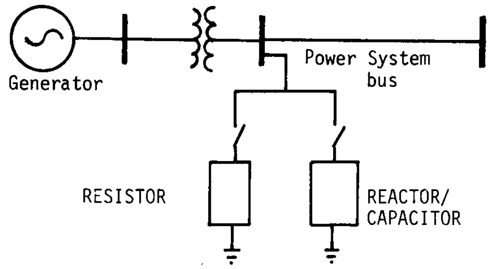

Fig. 1 Braking resistor, reactor/capacitor location for a generator.

The swing equation for the reference (r-th) machine is

$$M_r p^2\delta_r + D_r p\delta_r = P_{mr} - P_{er}(t) - P_{br}(t) \qquad (2)$$

Dividing the right hand sides of equations (1) and (2) by the respective inertia constants and subtracting one from the other, we get

$$p^2\delta_{ir} = \frac{1}{M_i}\,[P_{mi} - P_{ei}(t)] - \frac{1}{M_r}\,[P_{mr} - P_{er}(t)] - \frac{1}{M_i} P_{bi}(t) + \frac{1}{M_r} P_{br}(t) \qquad (3)$$

Here $\delta_{ir} = \delta_i - \delta_r$. Damping terms are neglected. The equation is rewritten as

$$p^2\delta_{ir} = L_i(t) - L_r(t) + b_i u_i(t) + b_r u_r(t)$$
$$= L_{ir}(t) + b^T u(t) \qquad (4)$$

where, $L_{ir}(t) = L_i(t) - L_r(t)$

$$b_i = -\frac{1}{M_i}, \quad b_r = \frac{1}{M_r}$$

$$P_{bi}(t) = u_i(t), \qquad P_{br}(t) = u_r(t)$$

Since the power absorbed by the brakes have an upper limit (say 1 p.u.), the constraint on the control can be written as

$$0 \le u_i(t) \le 1 \qquad i = 1, 2, ..r, ...n \qquad (5)$$

The control problem for transient stability can be formulated as: Given the system of equation (4), find control u(t) subject to constraint (5) on all its elements, so that following a disturbance the steady state value of δ_{ir} and its derivative $\dot{\delta}_{ir}$ respectively are brought to

$$0 \le \delta_{ir}(t_f) \le \pi/2$$
$$\dot{\delta}_{ir}(t_f) = 0 \qquad (6)$$

in the fastest possible time, or minimizing the cost index

$$J = \int_{t_o}^{t_f} dt \qquad (7)$$

The cost index J in this problem is simply $t_f - t_o$. Minimization of J implies reaching the targetted stable condition in minimum time.

Extending the analysis presented in reference [8], the quasi-optimal braking control strategy can be written as

$$u_i^*(t) = \begin{cases} 1 \text{ (resistor on)} & \text{if } \Sigma_b > 0 \\ 0 \text{ (reactor/capacitor on)} & \text{if } \Sigma_b < 0 \end{cases} \qquad (8)$$

where,

$$\Sigma_b = \Upsilon_1 \cup \Upsilon_2 \cup \Upsilon_3$$

$$\Upsilon_1:\ \delta_{ir} - \frac{\dot{\delta}_{ir}^2}{2[L_{ir} - \sum_{i,r} b_k \ \mathrm{sgn}\{\dot{\delta}_{ir}\}]} = 0, \quad \dot{\delta}_{ir} > 0$$

$$\Upsilon_2:\ 0 \le \delta_{ir} \le \pi/2, \qquad \dot{\delta}_{ir} = 0 \qquad (9)$$

$$\Upsilon_3:\ \delta_{ir} - \frac{\dot{\delta}_{ir}^2}{2[L_{ir} - \sum_{i,r} b_k \ \mathrm{sgn}\{\dot{\delta}_{ir}\}]} - \pi/2 = 0, \quad \dot{\delta}_{ir} < 0$$

If the reference machine is very large compared to the other machines, the part of L_{ir} due to the reference machine in equation (4) will be negiligible. In the absence of a brake facility on the reference machine, algorithm (8) and (9) will give the control entirely in terms of variables local to each machine.

<u>The Excitation Control Strategy</u>

The synchronous generator swing equation given in equation (1) can be rewritten as

$$Mp^2\delta = P_m - (v_d i_d + v_q i_q) \qquad (10)$$

The subscript i has been dropped for simplicity. The bracketted quantity is the output power of the machine. Subscripts d and q refer to direct and quadrature axes quantities; i and v are currents and voltages respectively.

Differentiate both sides of equation (10) with respect to time to get

$$Mp^3\delta = -v_d p i_d - v_q p i_q - i_d p v_d - i_q p v_q \qquad (11)$$

Here, $\dot{P}_m = 0$ since no governor action is considered. From basic machine equations we have [15]

$$v_d = x'_q i_q + e'_d \qquad (12)$$
$$v_q = -x'_d i_d + e'_q \qquad (13)$$
$$pe'_q = (E_{fd} - e'_q) / T'_{do} \qquad (14)$$
$$pe'_d = -e'_d / T'_{qo} \qquad (15)$$

In the above, ' represents the transient quantities, T'_{do} and T'_{qo} are the open circuit field time constants. Using the fact that

$$pe'_q = x'_d p i_d \qquad (16)$$
$$pe'_d = x'_q p i_q \qquad (17)$$

and substituting (12) - (17) in (11) and after some algebraic manipulations we can write

$$p^3\delta = L_e(t) + b_e(t)\,u(t) \qquad (18)$$

where

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

$$b_e(t) = -v_d / M x'_d T'_{do}$$
$$u(t) = E_{fd}$$

The control u(t) is limited by the excitation ceilings given as

$$|u(t)| \le k \qquad (19)$$

Introducing the subscripts i and r for the i-th and r-th (reference) machines and writing equations similar to (17) for each, we can get

$$p^3\delta_{ir} = L_{ir}(t) + b(t)\, u(t) \qquad (20)$$

where
$$L_{ir} = L_{ei}(t) - L_{er}(t)$$
$$b(t) = [\, b_{ei}(t) \quad b_{er}(t)\,]^T$$
$$u(t) = [u_i(t) \quad u_r(t)\,]^T$$

The time optimal control for system (20) subject to constraint (19) on each control can be expressed as follows [15]:

$$u_i^*(t) = -k \qquad \text{if } \Sigma_1 > 0$$
$$u_i^*(t) = k \qquad \text{if } \Sigma_2 < 0 \qquad (21)$$
$$u_i^*(t) = k \operatorname{sgn} \Sigma_e, \text{ otherwise}$$

where,

$$\Sigma_1 = \delta_{ir} - \delta_{ir} \cdot \dot{\delta}_{ir} + \frac{1}{3\alpha^2} (\ddot{\delta}_{ir})^3 - \pi/2$$
$$\Sigma_2 = \Sigma_1 + \pi/2$$
$$\alpha = \begin{cases} u_{i\,max} & \text{if } \dot{\delta}_{ir} > 0 \\ u_{i\,min} & \text{if } \dot{\delta}_{ir} < 0 \end{cases} \qquad (22)$$

$$\Sigma_e = \delta_{ir} - \frac{(\dot{\delta}_{ir})^2}{2\,[L_{ir} - \sum_{i,r} b_j k \,.\, \operatorname{sgn}\{\dot{\delta}_{ir}\}\,]}$$

b_{ei} and b_{er} are considered to be negative in strategies (21) and (22).

Finally, the additional stabilizing signal $u_s(t)$ in the voltage regulator-exciter loop is expressed as

$$u_s(t) = k_e \Upsilon \qquad (23)$$

where Υ is Σ_1, Σ_2 or Σ_e as the case may be. k_e is selected by trial and error so that the exciter is driven to the ceilings in a bang bang manner when the disturbance is large.

If each machine in the system is assumed to be controlled ($0 \leq \delta\ (t_f) \leq \pi/2$) it is possible to simplify the entire control strategy and the stabilizing control in such a case can be expressed simply as

$$u_s(t) = k_e \Sigma_e \qquad (24)$$

where Σ_e is given in equation (22). Again, if the reference machine is large and there is no excitation controller on it, equation (24) gives a strategy which depends on local variables only.

SIMULATION STUDIES

The proposed control strategies were tested on a 4 machine power system shown in Figure 2. System data are given in reference [7].

Symmetrical 3-Φ faults were simulated on buses 2, 3 and 4. Generator #1 was considered to be the reference machine. Results of fault studies on bus #3 are presented in the following. Machine #3 is the most severely disturbed generator and the responses of this machine with various control strategies are given.

Each machine in the system is simulated through a fourth order model -- the electromechanical equation and the d-q axes flux decay equations. The excitation system of each generator is represented by a fourth order model . The dynamic equations are converted to algebraic ones and solved through an iterative trapezoidal integration technique. Intermediate load flow calculations are done through a fast decoupled technique.

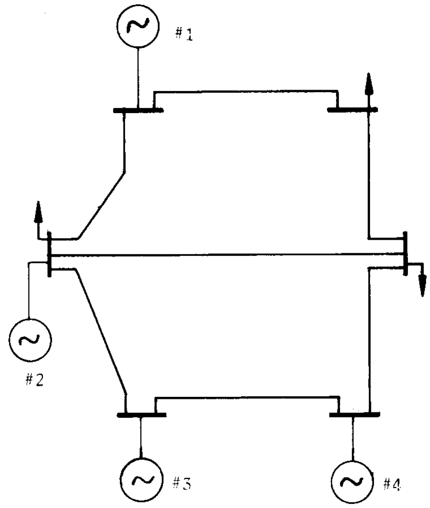

Fig. 2 Power system configuration

Three dynamic braking configurations with and without excitation controls are studied. These are

- Only resistor brake
- Resistor and reactor
- Resistor and capacitor

In the first strategy, the resistor should be switched in when $\Sigma_b > 0$. There is no control action when $\Sigma_b < 0$. In the second and third, reactor and capacitor will be switched in respectivly when $\Sigma_b < 0$. No two controls will be switched in simultaneously. The brake will be discontinued when the switching function Σ_b is within a deadband. This deadband also applies in respect of switching of resistor, reactor or capacitor. A value of 0.008 for the deadband has been arrived at by trial and error such that a stable response is obtained without much of unnecessary switchings. The value of conductance and susceptances of the brake elements were assumed to be 1 and 10 p.u. respectively as in reference [7].

Generator #1 in Fig. 2 is extremely large. This study considers that it is not equipped with any brakes. This makes the braking strategy given by equations (8) and (9) a function of only quantities local to individual generators. It is also assumed that generator #1 has no additional excitation controller. Since the application of resistor and reactor/capacitor brake will control the initial larger swings, the restriction on rotor angle swings in excitation strategy is not required. The excitation control then can be obtained from equation (24) which is a simpler version of the one given in (21).

Resistor Brake and Excitation Control

The rotor angle variations of machine #3 is given in Fig. 3 following a fault at the terminal of the machine. Curve a is with no control. The uncontrolled system is unstable. Curves b and c are with only braking resistor, and braking resistor plus excitation control respectively. Only braking resistor (no reactor, capacitor) captures the first swing instability, but the system falls into sustained oscillatory mode. The excitation control provides a smooth transition to normal operating condition as shown by curve c.

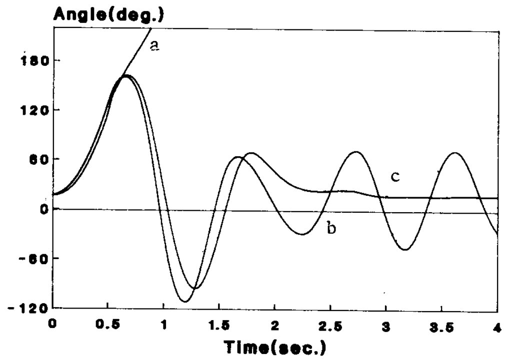

Fig. 3 Angle-time characteristics of machine #3 following a 3-ϕ fault on bus # 3 cleared after 0.52 sec., with (a) no control (b) with resistor brake only, and (c) with resistor brake and excitation control.

With the selected deadband of 0.008 on the switching function Σ_b, the optimal switching strategy given by equations (8) and (9) switches the resistor twice into the system. Out of these two switchings, the first one is for a relatively longer duration (about 1/2 sec). Figure 4 shows the angle variation of machine #3 if the brake is switched in only the first time. The system is first swing stable but extremely oscillatory (curve b). The excitation control though does not seem to be very effective in the first cycle of the transient, provides sufficient damping to eliminate all the oscillations in about 3.5 secs. This demonstrates that some of the switchings can be eliminated with a properly coordinated excitation strategy. Note that one switching of resistor can be simulated approximately by relaxing the deadband on Σ_b.

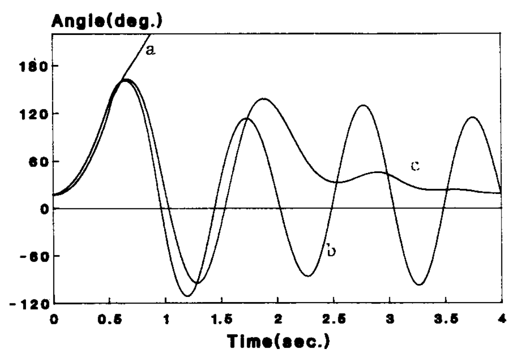

Fig. 4 Angle variations of machine #3 for the fault condition of Fig. 3, with (a) no control (b) braking resistor switched only once, and (c) braking resistor switched once plus excitation control.

Resistor-reactor Brake and Excitation Control

When the generator ceases to accelerate, the braking resistor is switched off. The machine is in deceleration mode when $\Sigma_b < 0$. Switching in the reactor reduces the terminal voltage of the machine, reducing the output power and thus reducing the deceleration of the machine.

Figure 5 shows the rotor angle variation for the faulted conditions studied when the optimal resistor-reactor switching strategy is used. Curve a is with no control, b with resistor-reactor control, and c with resistor-reactor plus excitation control.

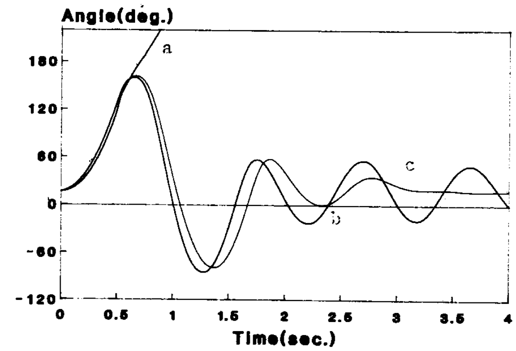

Fig. 5 Angle time characteristics of machine #3 following the fault, with (a) no control, (b) optimum resistor-reactor control, and (c) resistor-reactor and excitation control.

Comparison of curves b in Figures 3 and 5 clearly shows that the resistor-reactor control reduces the electromechanical transients significantly. The excitation control gives a very good transient elimination as depicted in Fig. 5c. Figure 6 shows the variation of frequency of generator #3 corresponding to the case of Fig. 5.

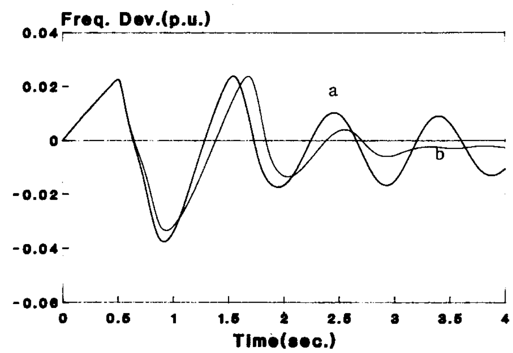

Fig. 6 Frequency variation characteristics corresponding to Fig. 5 with (a) resistor-reactor control, and (b) resistor-reactor and excitation control.

Resistor-capacitor Brake and Excitaion Control

A very good transient response is obtained when the reactor is replaced by a capacitor in the dynamic braking strategy. Figure 7 gives the responses with resistor-capacitor (curve b) and resistor-capacitor plus excitation control strategies (curve c). Comparison of Fig. 5 (curve b) and Fig. 7 (curve b) shows that the resistor-capacitor strategy controls the transients much better than the resistor-reactor scheme. The first swing deceleration is completely stopped by the resistor-capacitor strategy and subsequent swings are also reduced. The additional excitation control gives a very smooth transition to normal operating condition (curve c). It can be seen that the oscillations are completely eliminated in about 2.5 sec.

Figures 8 and 9 show the terminal voltage and field voltage variations with resistor-capacitor (curve a) and resistor-capacitor plus excitation control (curve b) respectively. The excitation control reduces the sharp variations in terminal voltage of the machine by slowing down the transients. The terminal voltage recovery is achieved by a wider variation of field voltage (Fig. 9b) compared to that without excitation control.

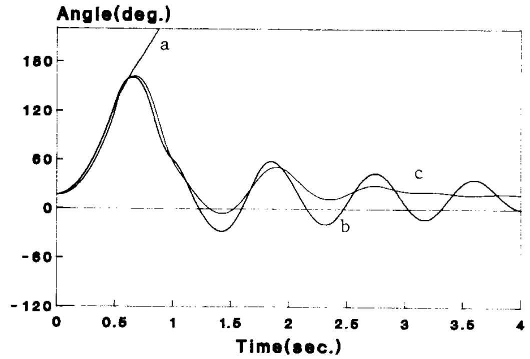

Fig. 7 Angle-time characteristics of machine #3 following a 3-ϕ fault, with (a) no control, (b) resistor-capacitor brake, and (c) resistor-capacitor plus excitation control.

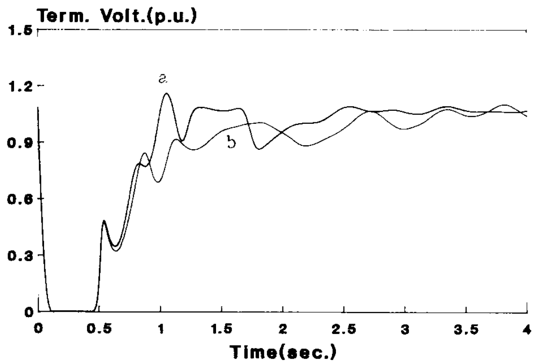

Fig. 8 Terminal voltage of machine #3 corresponding to Fig. 7, with (a) resistor-capacitor brake, (b) excitation control in addition to (a).

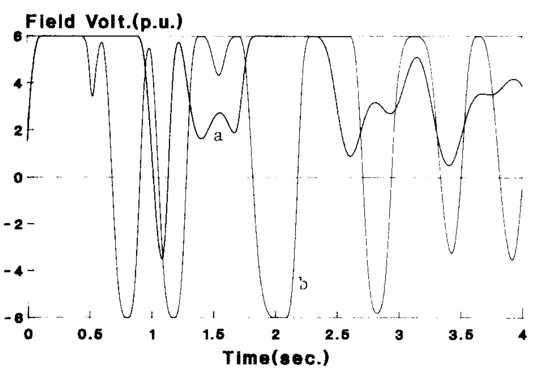

Fig. 9 Field voltage variation of machine #3 corresponding to Fig. 7, with (a) resistor-capacitor control, and (b) resistor-capacitor plus excitation control.

Figure 10 gives a comparison of angle variations with resistor-reactor and resistor-capacitor strategies in the presence of excitation control on both. The co-ordinated resistor-capacitor and excitation control provides a very good transient control as shown by curve b.

Note that all the three generators (#2, #3 and #4) other than reference are assumed to be equipped with excitation controllers. The exciter of generator #3 contributes the most

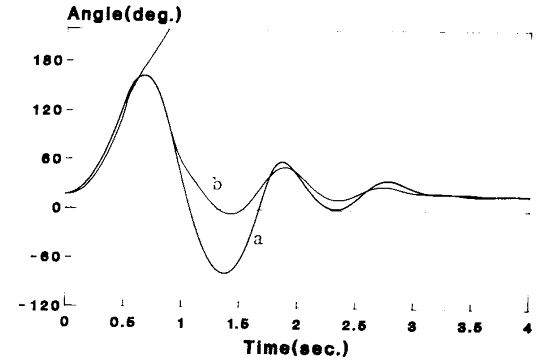

Fig. 10 Angle-time characteristics of machine # 3 following a 3-ϕ fault on bus # 3 cleared after 0.52 sec., with (a) resistor-reactor plus excitation control, (b) resistor-capacitor plus excitation control.

to the damping of transients for the particular fault, while contributions from those of #2 and #4 are marginal. The combined effect of exciters on #2, #3 and #4 is slightly better than that of #3 alone. This has been observed for almost all the cases studied.

CONCLUSIONS

Optimal strategies for controlling first swing instability as well as subsequent oscillations in the system are presented. Three braking strategies -- resistor, resistor-reactor and resistor-capacitor, are proposed to enhance transient stability while a nonlinear excitation control removes the oscillations following a large disturbance. It was observed that a co-ordinated resistor-capacitor strategy with the excitation control provides the best response.

All the proposed control strategies are expressed as functions of system states and other measurable quantities. Under certain conditions, the controls can be expressed in terms of variables local to each machine in the system. This makes online implementation of the control strategies easy.

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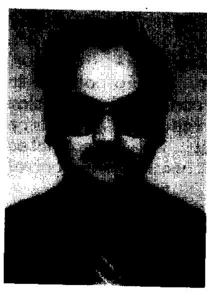

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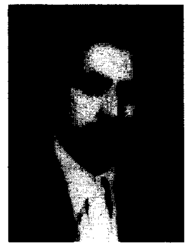

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