A CLOSED-LOOP QUASI-OPTIMAL DYNAMIC BRAKING RESISTOR AND SHUNT REACTOR CONTROL STRATEGY FOR TRANSIENT STABILITY

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Abstract

A control strategy for dynamic braking resistor and shunt reactor is proposed for stabilization of power systems when subjected to large disturbances. The time optimal control is derived as a function of synchronous machine power, its rotor angular position and speed deviation. The response for a single machine system with the proposed control has been compared with that from the time optimal solution obtained through the steepest descent method. The strategy has also been tested on two multimachine systems. Results indicate that the proposed strategy provides a simple and effective method of stabilization under transient emergency conditions.

INTRODUCTION

Dynamic braking is known to be one of the very effective methods for transient stability improvement. The braking resistor can be viewed as a fast load injection to absorb the excess transient energy of an area which arises due to severe system disturbances.

Practical use of dynamic braking resistors for transient stability improvement has been reported in the USSR [1,2] and also in Japan [3]. In these cases braking resistor has been used repeatedly to absorb the excess transient energy. Braking resistors have been successfully used in the Peace River 500-kV transmission systems and the Four Corner Plants of Arizona Public Service Company [4,5]. A 1400 MW dynamic braking resistor is in use at the BPA's Chief Joseph substation [6]. Switching in and out of the braking resistors in these installations are done mostly on predetermined, open loop strategies.

A number of work has been reported ranging from theoretical studies and computer simulations [7-11] to testing of various switching algorithms with micromachines and test systems [12-16]. The real problem has been and still is the determination of easily implementable best or optimal switching strategies. While a braking strategy depending only on machine speed deviation alone is easy in terms of realization [16,17], the determination of the threshold values is not straightforward. Optimum strategies for determination of switching times are, naturally, complicated [10,11] and are handicapped in terms of online applications.

Aliyu [17] presented an interesting local control strategy which switches a braking resistor and a shunt reactor alternately depending on velocity deviations. The resistor absorbs the excess energy while the machine accelerates and the reactor significantly reduces the output power when it declerates. The switching strategy was determined from an estimate of the critical clearing time through Liapunov's direct method which again is obtained from reduction of the multi-machine system to a single machine equivalent. The strategy requires off-line computation, system reduction etc. making it not a very attractive method from online application viewpoint.

In this article a closed-loop quasi-optimal scheme for switching of braking resistor and shunt reactor is proposed. For online implementation the control strategy requires measurement of machine power, angular position and speed deviation only. Results obtained for a single machine system has been compared with those from a standard optimization procedure. Two multimachine systems, including the system considered in [17], have been examined and the proposed control strategy has been found to be very effective. The initial results have been reported in another publication [18].

THE SINGLE MACHINE INFINITE BUS SYSTEM

System Configuration

The braking control strategies have been developed first for a simple system - a single generator feeding an infinite bus through a double circuit transmission line. The theory is then extended to include each machine in a multimachine system. The single machine system is simpler in terms of dynamic representation and hence verification of the control strategies derived against any standard procedure is easier. The braking resistor and shunt reactor have been connected to the high tension side of the generator transformer as shown in Fig. 1.

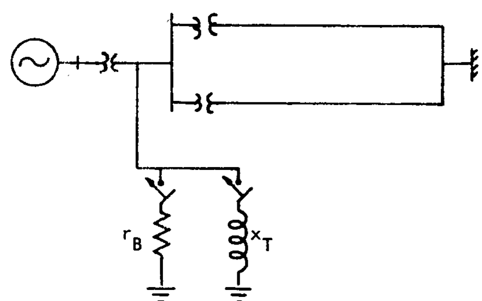

Fig. 1. Single machine infinite bus system.

In transient stability studies the period of interest is very short and hence the dynamics of the system can be represented approximately by the generator swing equation only, given as

$$M\frac{d^2\delta(t)}{dt^2} + D\frac{d\delta(t)}{dt} = P_m - P_e(t) - P_b(t) \qquad (1)$$

Here P_m, P_e, P_b are the mechanical input, electrical output power and power absorbed by the braking resistor respectively. δ is the rotor angular position; M and D are the generator inertia and damping coefficients respectively.

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By switching the resistor in and out of the circuit, the power absorbed $P_b(t)$ can be varied between maximum and zero respectively. It is assumed that at one time either the braking resistor or the shunt reactor will be switched in. Switching the resistor in is a load injection, and the shunt reactor insertion amounts to reduction in power transferred (P_e) by the machine.

Statement of the Control Problem

Following a disturbance in the system, if the trajectory remains in the region of attraction of the equilibrium (operating) point then the system is said to be stable. If the disturbance is large, as in the case of a severe fault or loss of a large load, the trajectory may leave the boundary of the stability region. If action is not taken quickly enough to bring the trajectory back to the domain of attraction of the post disturbance system equilibrium point, the synchronous machines will run out of step. So, the performance measure to be minimized in such problems can be selected to be "time". For normal operation of the machine, the steady state speed variation should be zero while the rotor angle will be limited between $-\pi/2$ (motor operation) and $\pi/2$ (generator) radians. This specifies the largest state in the formulation of the optimization problem.

Assuming $\delta(t) = x_1$ and $\dot{\delta}(t) = \omega(t) = x_2$, equation (1) can be broken up into the following two equations

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= p(x) + bu(t) \end{aligned} \tag{2}$$

where $p(x)$ contains the accelerating power and control u is the power absorbed in the braking resistor (p_b). The damping power may be included in $p(x)$ or may be neglected since it is very small. The control u is constrained by upper and lower bounds as follows

$$0 \leq u(t) \leq 1 \tag{3}$$

Switching in the shunt reactor will reduce the output power and will be reflected in $p(x)$. The control $u(t)$ is zero under this condition.

The optimization problem then can be stated as:

Given the system described by equation (2), find control $u(t)$ which minimizes the cost index

$$J = \int_{t_o}^{t_f} dt \tag{4}$$

and transfers the system to initial (perturbed) states to the target states (considering only generator action)

$$\begin{aligned} 0 \leq x_1(t_f) &\leq \pi/2 \\ x_2(t_f) &= 0 \end{aligned} \tag{5}$$

at the same time satisfying the inequality constraint (3).

Derivation of the Closed-Loop Control Strategy

In general, the solution of the above mentioned minimum time problem is not simple because of the nonlinear term $p(x)$ in equation (2). Closed-loop solution for u, as such, is further more complicated, if at all possible. In order to arrive at a closed loop scheme we do the following analysis.

The term $p(x)$ comprises of the machine accelerating power and is a measurable quantity. Assuming that the system is controllable, the accelerating power should be less than the power absorbed in the brake, or

$$|p(x)| \leq bu(t) \tag{6}$$

Let us now assume that at time $t = t_o$, $p(x) = p_o$ a known quantity. The system equation can then be written as

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= p_o + bu \end{aligned} \tag{7}$$

This is similar to the so called double integral plant covered in standard texts [19] with an additional constant term with the control variable. The control strategy for this system can be easily shown to be

$$u^*(t) = \begin{cases} 1, & (x_1, x_2) \subset R_1 \\ 0, & (x_1, x_2) \subset R_2 \end{cases} \tag{8}$$

Regions R_1 and R_2 are divided by the switch curve Σ given as

$$\Sigma = \gamma_1^o \cup \gamma_2 \cup \gamma_3^o \tag{9}$$

$$\gamma_1^o : x_1 - \frac{x_2^2}{2[p_o - b.\text{sgn}\{x_2\}} = 0, \qquad x_2 > 0$$

$$\gamma_2 : 0 \leq x_1 \leq \pi/2, \qquad x_2 = 0$$

$$\gamma_3^o : x_1 - \frac{x_2^2}{2[p_o - b.\text{sgn}\{x_2\}]} - \pi/2 = 0, \qquad x_2 < 0$$

Because of oscillatory nature of the system, the states will not continue on the switch curve and hence this possibility is not included in (8). The switch curves at $t = t_o$ are shown in Fig. 2. For any state in R_1, expression (9) will give a value of $\Sigma > 0$ and vice versa.

Once the control is found at $t = t_o$, this is applied for a period Δt and at $t = t_1$, the quantity $p(x)$ is checked. If at that time it assumes a value p_1, the control decision at $t = t_1$ is made by replacing p_o by p_1 in equation (9). The process is repeated until the trajectory reaches sufficiently close to the target state when it is discontinued. The control strategy is determined from a set of moving switch curves, which are shown in Fig. 2. Here an arbitrary target set between limits σ_1 and σ_2 on the x_1 axis have been shown. Note that $p(x)$ is a measure of the accelerating power which we have assumed smaller than the brake power. This limits the region covered by the moving curves. The idea of moving switch curves for excitation control was introduced in reference [20].

It has to be made sure that there is no switching back and forth of the control, because of sudden changes in $p(x)$, in the area where the moving curves lie. Provision of a deadzone can take care of this. This deadzone can be so selected that the control is also discontinued when the trajectory is near the target state. The strategy (8) and (9) implies that if the trajectory is to the right of the switch curve ($\Sigma>0$) apply the braking resistor otherwise switch the reactor. If the states are in the deadzone $|\Sigma| < \epsilon$, there will be no control action.

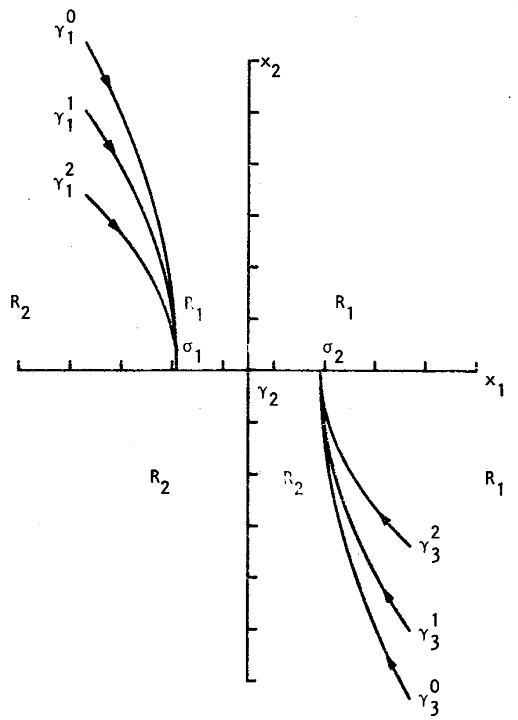

Fig. 2. The moving switch curves.

Results

The single machine infinite bus system given in Fig. 1 was modelled for testing the proposed algorithm. A symmetrical three phase fault on the high tension side of a line transformer cleared by opening one of the lines was simulated. The critical clearing time for this fault was 0.2 secs.

The proposed control strategy was evaluated by comparing the response with that from a standard optimization technique. A steepest descent algorithm modified to include inequality constraint [21] was used to solve the time optimal control problem. Since the time optimal control for the system given by equation (2) is of bang bang nature, it was necessary to solve for the switch times only as the control variable. The details of the optimization procedure is given in Appendix A.

Figure 3 shows the rotor angle variation of the synchronous machine for a three phase fault of 0.21 seconds duration. Responses are recorded for three cases - without control, with the proposed quasi-optimal control and with optimal control obtained through the steepest descent algorithm. It can be seen from the plots that the proposed closed loop control gives a response which is almost as good as that found through the iterative (open loop) optimal scheme. The advantage of the proposed scheme, as mentioned, is that the control is directly obtained in terms of a few measurable quantities viz, the rotor angular position, speed deviation and power of the machine. The data for the generator are given in Appendix B.

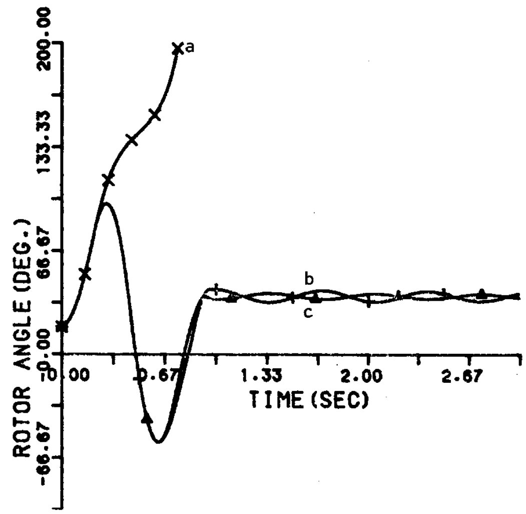

Fig. 3. Rotor angle variation of the synchronous generator following a 3-ϕ fault cleared after 0.21 secs. Responses are with (a) no control (x), (b) proposed quasi-optimal control (+) and (c) optimal control found through steepest descent method (Δ).

MULTIMACHINE SYSTEMS

Derivation of the Control Strategy

The quasi-optimal control strategy derived in the previous section can be easily extended to multimachine systems. Since in a multimachine system the angle of each machine is measured w.r.t. a reference machine (real or fictitious), the algorithm involves the dynamics of the reference machine. Consider the swing equations of the ith and the r-th (reference) machines (neglect damping)

$$M_i \ddot{\delta}_i = P_{mi} - P_{ei}(t) - P_{bi}(t) \tag{10}$$

$$M_r \ddot{\delta}_r = P_{mr} - P_{er}(t) - P_{br}(t) \tag{11}$$

Divide the right hand sides by the corresponding inertia constants and subtract to get

$$\begin{aligned}\ddot{\delta}_{ir} &= \frac{1}{M_i}[P_{mi}-P_{ei}(t)] - \frac{1}{M_r}[P_{mr}-P_{er}(t)] \\ &\quad - \frac{1}{M_i}P_{bi}(t) + \frac{1}{M_r}P_{br}(t) \\ &= L_i(t) - L_r(t) - b_i u_i(t) + b_r u_r(t) \\ &= L_{ir}(t) + b^T u(t)\end{aligned} \tag{12}$$

where $\delta_{ir} = \delta_i - \delta_r$, $L_{ir}(t) = L_i(t) - L_r(t)$, $b = [-b_i \;\; b_r]^T$

$u(t) = [u_i(t) \;\; u_r(t)]^T$

Considering $\delta_{ir} = x_1$ and $\dot{\delta}_{ir} = x_2$, equation (12) can be broken up into two equations as in (2) and the controls obtained similar to those as given in equations (8) and (9), the term p(x) being replaced by L_{ir}. Normally, the reference machine is considered to be the largest machine in the system and the term $L_r(t)$ is small compared to $L_i(t)$ and hence can be neglected. If, in addition, the reference machine is not equipped with the brakes, then the control scheme for each machine is exactly the same as in the single machine case already discussed requiring measurements of only local variables.

Results

The control strategy derived is then tested with the following two multimachine systems.

System 1

The 4 machine system given in reference [17] is tested first with the dynamic resistor and shunt reactor control strategy suggested. This system was studied by Aliyu and El-Abiad with a control strategy derived from a single machine equivalent of a multimachine system and the estimate of the first switch made through energy function approach.

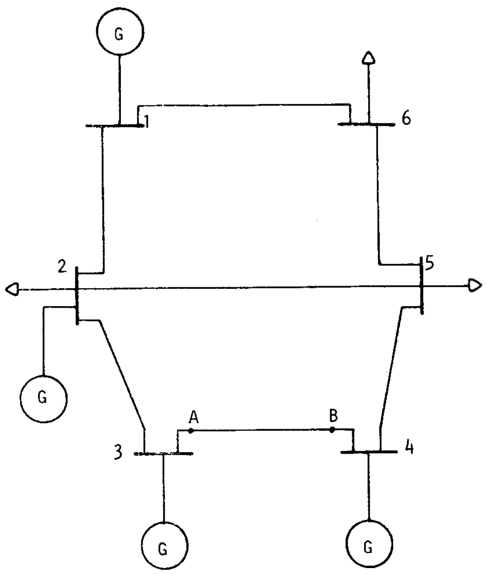

Fig. 4. Configuration of multimachine system 1 [Aliyu].

Figure 4 gives the power system considered by Aliyu. The data for this network is given in reference [22]. Three phase faults were simulated at A and B in Fig. 4 separately, cleared by opening a line between the respective buses. It was assumed that generators on both buses 3 and 4 are equipped with braking resistor and shunt reactor. The value of conductance (G_i) and susceptance (B_i) were considered to be 1 and 10 per unit respectively, as assumed by Aliyu.

Figure 5(a) shows the variation of all the machine angles when a 3-ϕ fault of 0.44 secs duration was applied at A. Angles of all the machines are w.r.t. machine # 1. As can be seen, machine # 3 exhibits first swing instability. Figure 5(b) shows the angle variation of machine # 3 only with the stabilizing controls. The response with Aliyu's control is marked +, while the proposed quasi-optimal control results into the response marked with Δ. The value of the switching function Σ evaluated at different points in the state space is shown in Fig. 6. A deadband of 0.08 per unit resulted in the response shown in Fig. 5(b). Figure 7 shows the response with the two control strategies (Aliyu's and the proposed one) when a 3-ϕ fault of 0.49 secs was applied at point B in Fig. 4. The uncontrolled system response (not shown) was unstable.

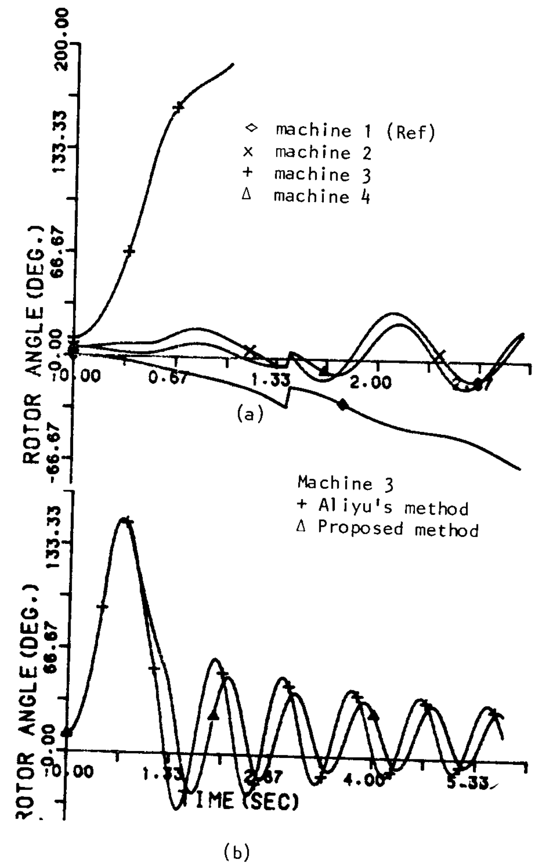

Fig. 5. Machine angles for a 3-ϕ fault of 0.44 secs duration on bus 3. (a) Response without any control; (b) response of machine # 3 with the two control strategies.

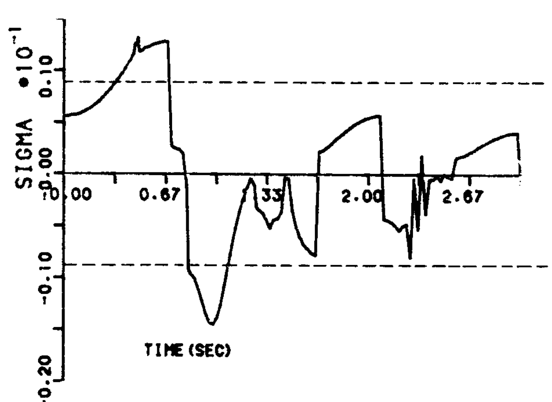

Fig. 6. Variation of the switching function with time. The deadzone is indicated by the dotted lines.

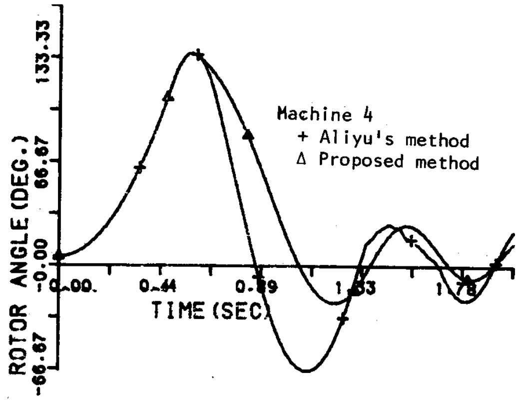

Fig. 7. Response of machine # 4 with the two control strategies for a 3-Φ fault of 0.49 secs on bus 4.

For the particular deadband selected, it can be seen that the transient response provided by the proposed strategy is superior. If the deadband is reduced, the response is slightly better but this means more switching. However, note that the point of comparison is not that the proposed strategy gives slightly better transient response after the instability is checked. The proposed control is obtained as a function of measurable quantities and is simpler in terms of online application.

System 2

The control strategy was also tested on a relatively larger system - an 11 machine reduced Bangladesh power network. The network diagram of this system is given in Fig. 8. The generator data are in Appendix B. The peculiarity of this system is that a double circuit relatively long line between TONH and ISUH connects two separate grid systems.

It is assumed that all the generators except the reference machine (GHMG) are equipped with control means. Thus the control is made entirely of local variables. Figure 9 shows the unstable system for a 3-Φ fault on KAPG bus, cleared after 0.42 secs. The critical clearing time is 0.4 secs. As can be seen, the generators at bus KAPG and SIKG exhibit first swing instability. The stable response with the brakes at KAPG and SIKG only are shown in Fig. 10. The values of conductance and susceptance were considered to be 1.0 and 10 p.u. The response given for the reference machine is in absolute angle (symbol ↑)

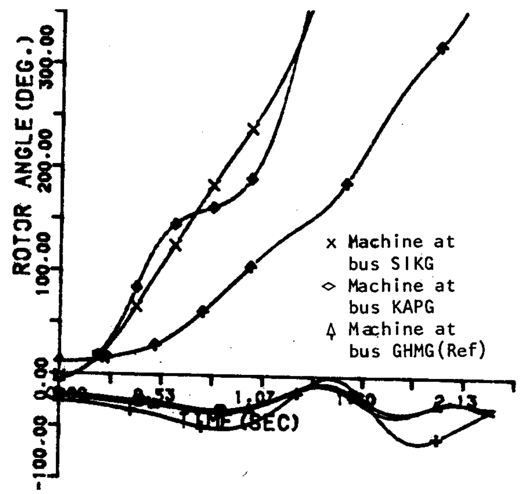

Fig. 9 Response without control for a 3-Φ fault on KAPG cleared after 0.42 secs.

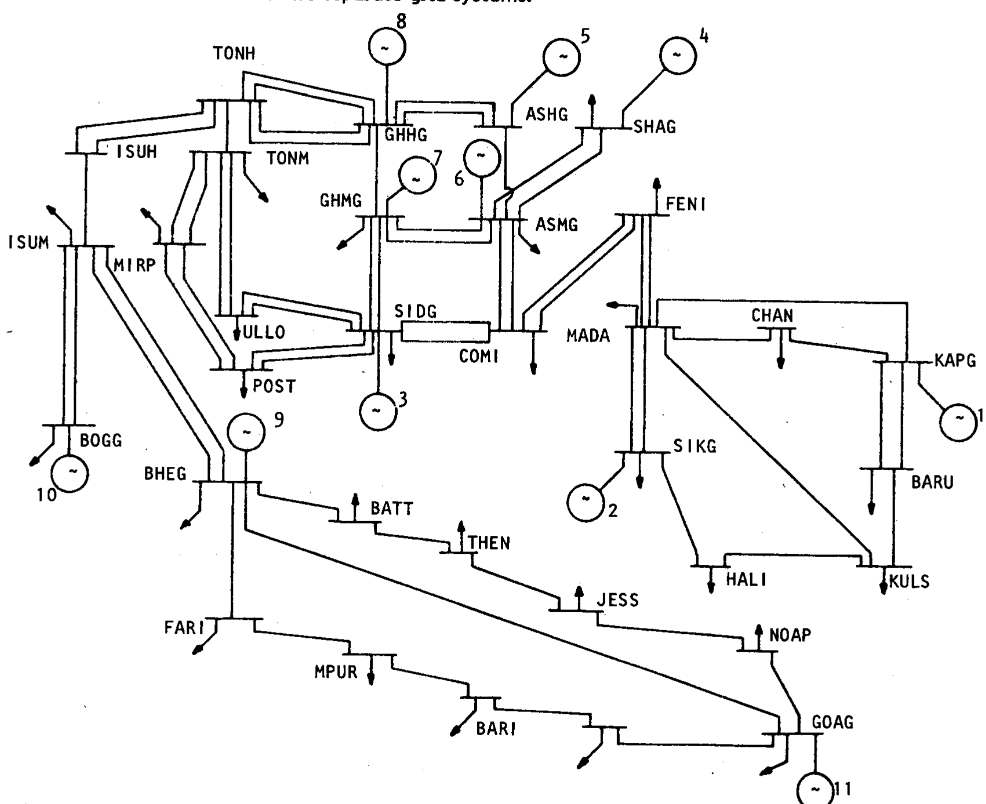

Fig. 8. An 11 machine reduced Bangladesh Power System.

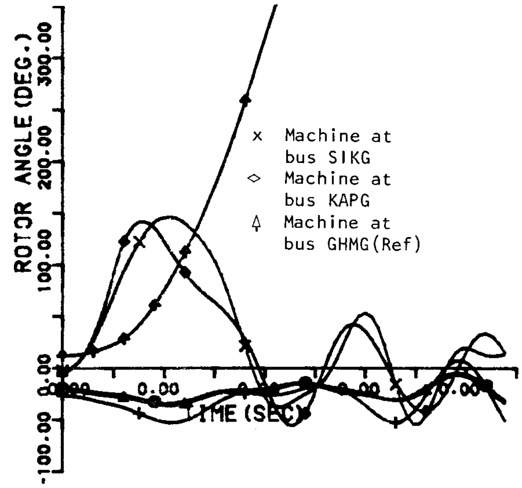

Fig.10 Stable system with the proposed control corresponding to the fault condition of Fig. 10.

A symmetrical fault for 0.44 secs on bus SIKG was also simulated. The critical clearing time was 0.43 secs for this fault condition. The control resulted in a stable system, control applied only at SIKG. Table 1 summarizes the braking resistor and reactor switchings for both the faults.

1. Fault on bus KAPG (critical clearing time 0.4 sec)

Machine at KAPG	Machine at SIKG
Fault on: 0.0-0.42 sec	
Brake on: 0.4-0.8 sec	Brake on: 0.4-1.0 sec
Reactor on: 0.81-1.2 sec	Reactor on: 1.1-1.5 sec

2. Fault at bus SIKG (Critical clearing time = 0.43 sec)

Fault on: 0.0-0.44 sec
Brake on: 0.42-0.64 sec
Reactor on: 0.65-1.28 sec.

Table 1 Summary of switching history for the Bangladesh Power System.

CONCLUSIONS

A simple quasi-optimum feedback strategy for transient stability augmentation through switching of resistor and reactors at the machine terminals is proposed. The control strategy requires measurement of only speed deviation, rotor angular position and power of the machines and has the potential of online implementation. The response for a single machine system has been found to match excellently that obtained through a standard optimization technique. The proposed scheme has also been tested with multimachine systems. It has been found that the strategy is very effective in controlling first swing instability.

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APPENDIX A

The Steepest Descent Method With Inequality Constraint

The state equations of the single machine infinite bus system is approximated as

$$\begin{bmatrix}\dot{x}_1 \\ \dot{x}_2\end{bmatrix} = \begin{bmatrix} x_2 \\ M^{-1}(P_m - Dx_2 - P_{max}\,\mathrm{Sin}\,x_1 - P_{brake})\end{bmatrix} \quad (A.1)$$

or $\dot{x} = f(x,u)$

where $P_{max} = E_i V_t / x'_d$

The time optimal P_{brake} is either 1 (maximum) or 0 (minimum). The state equations are discontinuous at switch times t_1, t_2, ... t_N which are to be found. The steepest descent algorithm given by Vachino [20] assumes a nominal switch time and then iteratively obtain the optimum switch time satisfying terminal and other constraints and minimizing cost index. The new control vector is then

$$d\xi = [\delta t_1, \delta t_2, \ldots\ldots \delta t_N]^T \quad (A.2)$$

The terminal constraints are that the final change of speed and acceleration should be zero. This gives

$$\psi_1 = x_2 = 0 \quad (A.3)$$

$$\psi_2 = M^{-1}[P_m - Dx_2 - P_{max}\sin x_1] = 0$$

The stopping condition is selected to be

$$\Omega = 1.2 - t_f \quad (A.4)$$

The cost index to be minimized is

$$\phi = -t_f \quad (A.5)$$

Introducing the Heaviside step function, the system equation for the period of interest (t_o, t_f) can be expressed as

$$\dot{X} = f_1[1-h(t-t_1)] + f_2[h(t-t_1)-h(t-t_2)] + \ldots f_N[h(t-t_{N-1})-h[t-t_N)] \quad (A.6)$$

where t_1, t_2, ... in (A.6) are the nominal values.

Taking first variation of (A.6) one can get

$$\delta\dot{X} = F_x \delta_x + L\delta\xi \quad (A.7)$$

and the adjoint equation is

$$\dot{\lambda} = -F_x^T \lambda \quad (A.8)$$

The variational equation for the control variable is given as

$$\delta\xi(t) = \sum_{s=1}^{N} W^{-1} L_s^T(t)\lambda_{\psi\Omega}(t) I_{\psi\psi}^{-1} d\psi \quad (A.9)$$

where

$$d\psi = [d\psi_1 \ : \ d\psi_2]$$

$$I_{\psi\psi} = \sum_{s=1}^{N} \int_{t_{s-1}}^{t_s} \lambda_{\psi\Omega}^T(\tau) L_s W^{-1} L_s^T \lambda_{\psi\Omega} d\tau$$

$$\lambda_{\psi\Omega}^T(t) = \lambda_{\psi}^T(t) - \frac{\dot{\psi}(t_f)}{\dot{\Omega}(t_f)} \lambda_{\Omega}^T(t) \quad (A.10)$$

$$= \lambda_{\psi}^T(t)$$

W is a weighting matrix.

The terminal conditions on the adjoint vector is

$$\lambda_{\psi_1}(t_f) = \frac{\partial\psi_1}{\partial x}\Big|_{t_f} = [0 \quad 1]^T$$

$$\lambda_{\psi_2}(t_f) = \frac{\partial\psi_2}{\partial x}\Big|_{t_f} = [P_{max}\cos[x_1(t_f)] \quad D]^T \quad (A.11)$$

APPENDIX B: SYSTEM DATA

Parameters of the Single Machine System

$H = 3.0$	$E_i = 1.15$ p.u.
$f = 60$ Hz	$x'_d = 0.2$ p.u.
$P_m = 1.0$ p.u.	$D = 0.0055$ p.u.
$V_t = 1.0$ p.u.	$r_B = 1.0$ p.u.
	$x_T = 0.1$ p.u.

Other reactances are

Generator transformer = 0.1 p.u.
Line transformer, each = 0.1 p.u.
Line reactance, each = 0.3 p.u.

Generator Data for the Bangladesh Power System

Machine No.	H	x'_d (p.u.)
1	11.36	0.1481
2	3.6375	0.4658
3	4.4062	0.3997
4	9.1325	0.2030
5	12.16	0.100
6	17.82	0.1021
7	6.0795	0.2399
8	5.17	0.1659
9	4.32	0.3635
10	5.62	0.2186
11	15.69	0.0945

Discussion

T. K. Nagsakar and **C. S. Ramarao** (University of Petroleum and Minerals, Dharan, Saudi Arabia): The authors are to be commended for developing a closed-loop quasi-optimal scheme for switching of braking resistor and shunt reactor for stabilization of power systems when subjected to large disturbances. The control strategy requires measurement of speed deviation, rotor angular position, and power of the machines, and it has the potential of on-line implementation.

We would like to offer the following comments.

i) How is the performance of the quasi-optimal control suggested going to be affected in the presence of excitation regulator and governor-controlled mechanism?
ii) Have the authors carried out stability studies of the test systems with values of G and B other than those reported in the paper? If so, how are the transient swings affected by the variation of G and B?
iii) How is the selection of dead zone made by the authors?
iv) For the Multimachine System 2, all the generators except the reference bus generator are equipped with the quasi-optimal dynamic braking resistor and shunt reactor control, and the control is made entirely of local variables. The discussers' view is that the quasi-optimal control of the reference machine using its own variables will definitely improve the transient swings of the generators during large disturbances, especially when the transient disturbance is in the vicinity of the reference machine.

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A. H. M. A. Rahim and **D. A. H. Alamgir**: The authors wish to thank the discussers for their comments. The proposed control strategy of switching in and out of resistors and reactors is used to improve stability of a system following large perturbations. It is widely known that when the disturbances are large the excitation control is not effective and in many applications is even switched out. The authors tried an additional excitation control when the initial transients were over and found improvement in the subsequent swings. Detailed results will be reported in a later article. No studies have been made with governor-controlled mechanisms.

The response of the system depends very much on the values of G and B. The value of the resistor should be chosen such that it is capable of absorbing the bulk of the accelerating power under the worst conditions. Similarly, the value of B should be such that there is virtually no power transfer when the machine is decelerating. The test cases given in the paper with the particular values of G and B were for the sake of comparison with the reported results.

The value of the dead band was obtained by the trial and error method.

It is recognized that if all generators are equipped with brakes, the response will be better. However, not all the generators may have brakes. The authors indicated that if the reference machine is relatively large and has no brakes, the control strategy in effect involves variables local to each machine. Otherwise, the control for each machine will be functions of variables local to each machine in addition to those of the reference machine.

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