Optimal switching of dynamic braking resistor, reactor or capacitor for transient stability of power systems

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Abstract: Three dynamic braking strategies for transient stabilisation of a power system have been investigated. These involve resistor, resistor–reactor and resistor–capacitor switching, respectively. The switching strategies are obtained from an optimum feedback control law. The proposed controls were tested on a four-machine power system. It was observed that although all the optimal strategies were able to contain the first swing instability, the resistor–capacitor switching was the best for electromechanical as well as electrical transients control.

1 Introduction

The dynamic braking resistor has been known to be a useful tool in stabilising power systems following large disturbances in the system. The braking resistor can be viewed as fast load injection to absorb the excess transient energy of an area caused by a disturbance. It has generally been studied as a shunt resistor load connected at a generator site and its energy absorbing capacity is limited by the maximum temperature rise of the braking resistor material.

Dynamic braking resistors are in use in the USA, Japan and the USSR. The Peace River system, the Four Corner Plant of the Arizona Public Service Company and the Bonneville Power Administration in North America have experience using braking resistors [1, 2, 3]. Normally, switching of the resistors in these installations is done on the basis of open loop, predetermined strategies. A number of theoretical and computer studies on braking resistor switching strategies are reported in the literature [4, 5, 6]. Studies have also been reported on micromachines and other test systems [7, 8].

Aliyu proposed a braking resistor and reactor control strategy for transient state emergency problems of power systems [9]. The strategy is based on the switching of a braking resistor and shunt reactor alternately depending on velocity deviations. The resistor absorbs the excess energy when the machine accelerates and the reactor reduces the electrical output by depressing the terminal voltage when the machine decelerates. A state feedback optimal resistor–reactor switching strategy proposed in Reference 10 was found to be superior to Aliyu's [9].

Shunt capacitors, in addition to their property of limiting rapid or slow voltage declines, can help maintain transient stability of a system that would otherwise be unstable [11]. The presence of capacitors influence the dynamics of the system following a disturbance by modifying the network parameters. The voltage support provided tends to reduce the transmission angle variations.

This paper examines the possibility of stabilisation through resistor–capacitor brakes and compares its effectiveness with resistor–reactor and only dynamic resistor brakes. Stability with only a resistor brake is studied in detail. A comparison of the three braking strategies (resistor, resistor–reactor, and resistor–capacitor) indicates that the resistor–capacitor switching is most effective in controlling the electromechanical as well as electrical transients.

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2 Optimum switching strategies

The braking resistor and the shunt reactor or capacitor are normally connected to the high voltage side of the generator transformer as shown in Fig. 1.

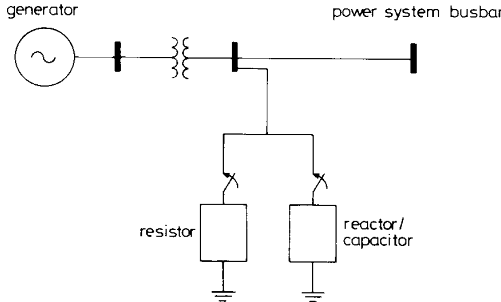

Fig. 1 *Dynamic braking resistor and reactor/capacitor configurations*

When the resistor is switched in, the reactor or capacitor is off and vice versa. Both the devices (resistor and reactor/capacitor) will be switched out when the initial swings are controlled. The switching strategy is obtained from the following analysis.

The electromechanical swing equation for the ith and the rth (reference) machine of a multimachine power system can be written as

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

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

where M, P_m, P_e, P_b are the inertia constant, mechanical input power, electrical output power and power absorbed by the brake, respectively. δ is the angular position of the rotor with respect to the stator MMF and operator p represents the time derivative d/dt. Dividing the right hand sides of eqns. 1 and 2 by the respective inertia constants and subtracting one from the other results in

$$p^2\delta_{ir} = L_{ir}(t) + b^T u(t) \tag{3}$$

where

$$L_{ir}(t) = M_i^{-1}[P_{mi} - P_{ei}(t)] - M_r^{-1}[P_{mr} - P_{er}(t)]$$
$$b = [-M_i^{-1} \quad M_r^{-1}]^T$$
$$u(t) = [u_i(t) \quad u_r(t)]^T = [P_{bi}(t) \quad P_{br}(t)]^T \tag{4}$$

δ_{ir} is the angle of ith machine with respect to the reference machine, or

$$\delta_{ir} = \delta_i - \delta_r \tag{5}$$

As the power absorbed by the brake can vary from zero to a maximum value (say 1), the constraint on each control variable can be expressed as

$$0 \leqslant u_i(t) \leqslant 1 \tag{6}$$

Following a large disturbance, relative rotor angle δ_{ir} may exceed the critical value rendering the system unstable. All available effort must then be exerted to bring the angle and also the speed near the equilibrium as quickly as possible. The performance index for such a problem can be written as

$$J = \int_{t_o}^{t_f} dt \tag{7}$$

where t_o and t_f are the initial and final times.

The optimal control problem is stated as: Given the system of eqns. 3, find the control $u(t)$ such that each of its elements satisfy eqn. 6 and the final values of rotor

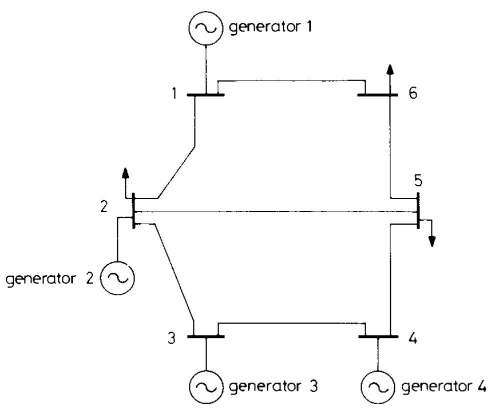

Fig. 2 *Single line diagram of four-machine system model*

angle and frequency satisfy

$$\dot{\delta}_{ir}(t_f) = \omega_{ir}(t_f) = 0 \tag{8}$$

$$0 \leqslant \delta_{ir}(t_f) \leqslant \pi/2 \tag{9}$$

at the same time minimising the cost index given in eqn. 7.

Following similar steps as given in Reference 10, it can be shown that the optimal switching strategy can be expressed as

$$u_i(t) = \begin{cases} 1 & \text{(braking resistor on)} \quad \text{if } \Sigma > 0 \\ 0 & \text{(reactor/capacitor on)} \quad \text{if } \Sigma < 0 \end{cases} \tag{10}$$

where

$$\Sigma = \Gamma_1 \cup \Gamma_2 \cup \Gamma_3 \tag{11}$$

$$\Gamma_1 : \delta_{ir} - \frac{\dot{\delta}_{ir}^2}{2[L_{ir} - \Sigma b_i \operatorname{sgn}\{\dot{\delta}_{ir}\}]} = 0 \quad \dot{\delta}_{ir} > 0$$

$$\Gamma_2 : 0 \leqslant \delta_{ir} \leqslant \pi/2 \quad \dot{\delta}_{ir} = 0$$

$$\Gamma_3 : \delta_{ir} - \frac{\dot{\delta}_{ir}^2}{2[L_{ir} - \Sigma b_i \operatorname{sgn}\{\dot{\delta}_{ir}\}]} - \pi/2 = 0 \quad \dot{\delta}_{ir} < 0$$

The switch curve at any instant of time is given in Fig. 3. If the states are on the right side of Σ, the resistor brake

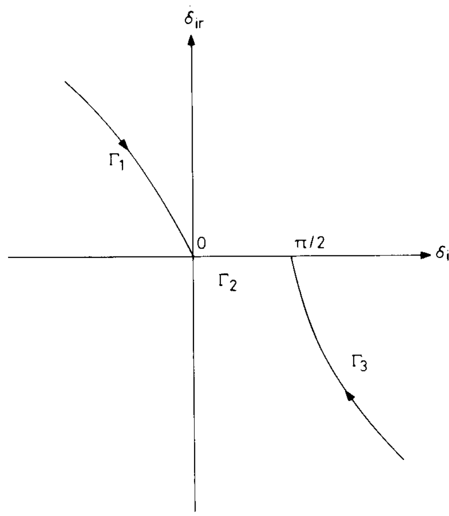

Fig. 3 *Switch curves in δ_{ir} and $\dot{\delta}_{ir}$ plane*

will be applied, otherwise the reactor or capacitor (as the case may be) will be switched in.

As can be seen, the switch function Σ given in eqn. 11 depends on the angle and frequency of each machine, in a multimachine system, with respect to those of the reference machine. If the reference machine is large compared with the rest of the units in the system, $L_r(t)$ (the component of L_{ir} because of the reference machine) is negligible. In the absence of a brake facility on the reference machine, the controls given by eqns. 10 and 11 depend on local variables only.

3 Results

The control strategies developed in the previous section were tested on the four-machine system given in Fig. 2. The system is taken from Reference 9 and data is provided in Appendix 6.1.

Generator 1, the largest machine in the system, was considered to be the reference. A number of faults were simulated on the system. Detailed results for only one fault condition on busbar 3 is given in this paper. It was assumed that only machines 3 and 4 have the provision of brakes. The assumption that the reference machine is large and is not equipped with brakes makes the control strategy very simple. The switching strategies depend only on the relative rotor angle, frequency and the other parameters of each machine. However, the control strategy given by eqns. 10 and 11 are general and apply for any multimachine power system irrespective of the size of the reference machine. A deadband of 0.008 on the switch functions was used. This means that there will be no control (resistor, reactor or capacitor switching) if $|\Sigma| \leqslant 0.008$. The values of G and B (conductance and susceptance of the elements of the brake) were considered to be 1 and 10 p.u., respectively, as used in Reference 9. The value of B for both reactor and capacitor was assumed to be the same.

The dynamics of the system uses a third-order machine model (electromechanical swing equation and d-q axes flux decays) with fourth-order exciter for each generator. The machine equations, and IEEE type 1 exciter used in the study are given in Appendix 6.2. The dynamic equations were converted to a set of algebraic relationships and were solved through an iterative trapezoidal integration technique. The fast decoupled method was used to perform the flow calculations of the 'network'.

3.1 Braking resistor only

The transient behaviour of the power system was examined when the generating units were equipped with dynamic braking resistor only. For a three phase fault of 0.52 s on busbar 3, the rotor angle time characteristics are shown in Fig. 4. Without any control (curve *a*) the

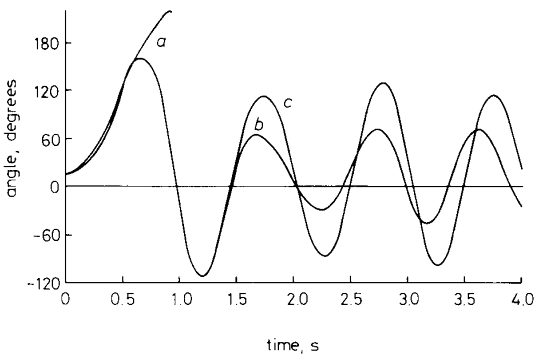

Fig. 4 *Angle-time characteristics of machine 3 following a fault of 0.52 s duration*

a No control
b Optimal control
c Resistor switched once

system is unstable. Optimal insertion of braking resistor results in a stable response shown by curve *b*. The resistor is switched in when Σ given in eqn. 11 is greater than 0.008.

The optimal strategy for the particular fault requires that the brake will be switched in and out several times before completely removing it. The first insertion of the resistor is for a relatively longer period. The response of the system was studied with the braking resistor switched in only once, the rotor angle characteristic shown in Fig. 4*c*. The system is stable but more oscillatory compared with the optimal switching case. Fig. 5 shows the terminal voltage variation characteristics. Curve *a* is with optimal switching and *b* with only one switch of the resistor. Only one switch, though it leads to more oscillations in both rotor angle and terminal voltage, may be preferable considering the physical limitations of switching such as wear. Note that the condition of only one switching can be simulated in the optimal scheme by choosing a larger value of deadband.

3.2 Resistor and shunt reactor control

Figs. 6 and 7 show the response of machine 3 when the resistor–reactor switching strategy is employed. In this strategy the resistor is switched in when $\Sigma \geqslant 0.008$. When $\Sigma \leqslant -0.008$ the reactor will be on. At no time will the two controls be in together. A comparison of the angle-time response made with resistor switching alone and resistor–reactor switching is given in Fig. 6. The response shown in curve *a* is with no control, *b* is with resistor–reactor control and *c* with resistor control alone. The resistor–reactor control is superior in terms of electromechanical swing because when the machine is decelerating, the reactor reduces the output power of the machine. The

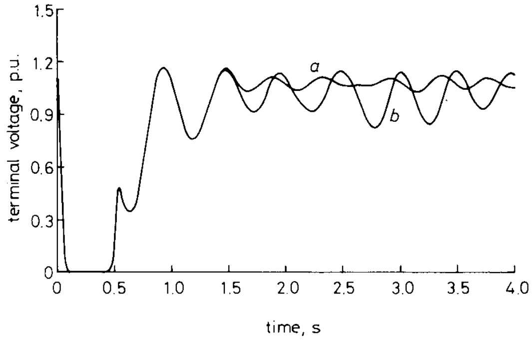

Fig. 5 *Terminal voltage variations of machine 3 corresponding to fault of Fig. 4*

a Optimal control
b One switching of resistor

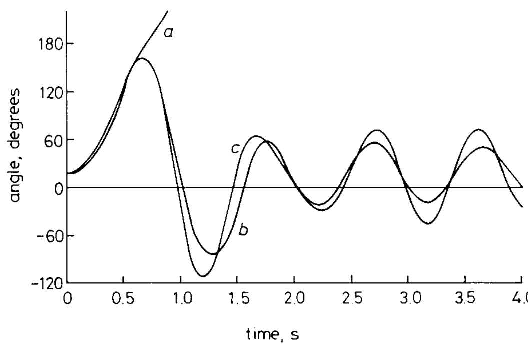

Fig. 6 *Rotor angle-time characteristics of machine 3 following fault of 0.52 s on busbar 3*

a No control
b Resistor–reactor control
c Resistor control only

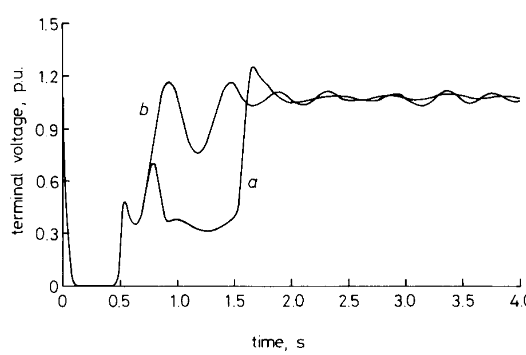

Fig. 7 *Terminal voltage characteristics of machine 3 corresponding to Fig. 6*

a Resistor–reactor switching
b Resistor switching pnly

reactor first comes in around one second, and it can be seen that the rotor angle retardation is controlled. No control is in effect after two seconds and hence the response subsequently is not greatly affected. Switching the reactor in depresses the terminal voltage as seen in Fig. 7, curve *a*. The voltage recovery is slow compared to that with resistor brake alone. Almost normal voltages are restored in about two seconds.

3.3 Resistor and capacitor control

Whether a shunt reactor or a capacitor is connected to the terminals of a machine, the net power absorbed by the element is zero. It is known that a capacitor improves the overall voltage profile following a fault when the voltage variations are steep. Braking resistors are switched in while the machine is accelerating. Once the resistor is switched out, the machine voltage rises rapidly. Switching a capacitor immediately after resistor braking will slow down the voltage surge and help recover the normal system performance. The effect of coordinated resistor–capacitor switching following a fault is investigated in the following.

Fig. 8 gives a comparison of rotor angle responses of resistor–reactor and resistor–capacitor controls obtained

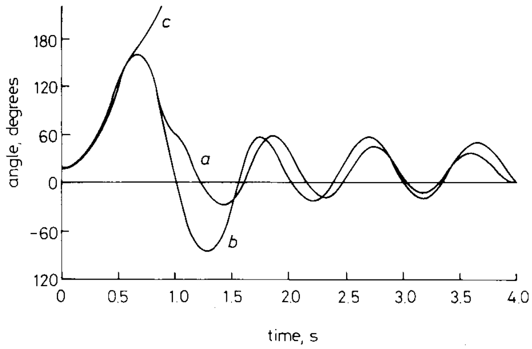

Fig. 8 *Rotor angle variations of machine 3 following a fault of 0.52 s on busbar 3*

a Resistor–capacitor switching
b Resistor–reactor switching
c No control

through the optimal switching strategy. Curve *a* is with resistor–capacitor control, *b* with resistor–reactor control, and *c* with no control. Figs. 9 and 10 show frequency and terminal voltage variation characteristics with resistor–capacitor (curve *a* in both the figures) and resistor reactor (curve *b*) switching. A closer look at the terminal voltage characteristics will show that the three major switchings of the capacitor around 0.8 s, 1.2 s and 1.7 s (Fig. 10*a*) reverse the voltage trends compared with resistor switching alone (Fig. 5*a*). The first capacitor switch is so effective that it reverses the frequency (Fig. 9*a*), reshaping the rotor angle characteristics given in Fig. 8*a*. The machine deceleration has been totally captured, slowing down the electromechanical transients very effectively. Compared with the resistor–reactor control (curve *b* in Figs. 8, 9 and 10) resistor–capacitor switching gives much superior response in the early part of the transients.

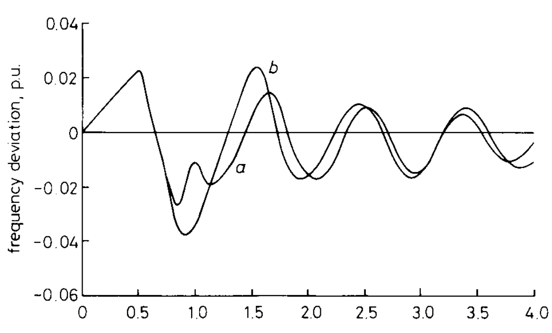

Fig. 9 *Frequency variation of machine 3 corresponding to Fig. 8*

a Resistor–capacitor switching
b Resistor–reactor switching

For the three phase fault on busbar 3, generator 3 is the most severely disturbed machine in the system. Generator 1 is an almost infinite machine and hence its

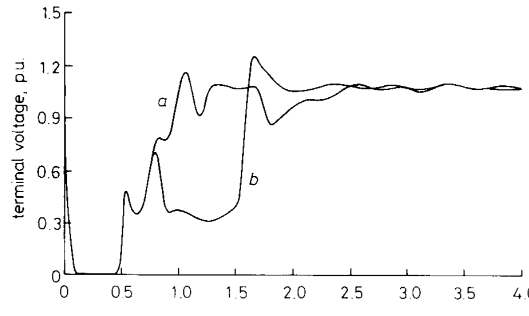

Fig. 10 *Terminal voltage variations of machine 3 corresponding to Fig. 8*

a Resistor–capacitor switching
b Resistor–reactor switching

response is unaffected. In the absence of any control, generators 2 and 3 also eventually run out of step. With any of the brake controls, the swing of generator 2 is not large. The maximum first swing generator 4 undergoes is about 85° (from 5 to −80) when only resistor brakes are applied. With the resistor–reactor brake combination, the maximum swing is about 44° (from 4 to −40). The transient response is again better with resistor and capacitor switching. As the general nature of the transients is similar to those of machine 3, the response curves for machine 4 are omitted.

4 Conclusions

Comparison of resistor, resistor–reactor, and resistor–capacitor switching for transient stability of a multi-machine power system is investigated. Although all the optimal strategies are able to control the first swing instability, resistor–capacitor switching provides the best response in terms of electromechanical as well as electrical transients control. The resistor–reactor strategy is better than resistor braking alone in terms of electromechanical oscillations. As expected, the terminal voltage characteristics are the worst with the resistor–reactor strategy. The optimal strategies proposed are simple, require only a few measurements and hence can be implemented online.

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6 Appendixes

6.1 Appendix A

Table 1: Parameters of the 4 machine system of Fig. 2.

(a) Line data

Line		Impedance	
From	To	*R*	*X*
1	2	0.05	0.20
2	3	0.10	0.50
3	4	0.20	0.80
4	5	0.10	0.30
5	6	0.20	0.40
6	1	0.10	0.15
2	5	0.20	0.50

(b) Synchronous machine data

Generator	At busbar	Rating	*H*	X_d (p.u.)	*D* (p.u.)
1	1	100	95.3	0.004	0.00265
2	2	15	1.498	1.0	0.0318
3	3	40	2.997	0.50	0.0066
4	4	30	2.0	0.40	0.0016

Standard values of other parameters were assumed

6.2 Appendix B

The dynamic model of each synchronous machine contains the following equations:

$$M\frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} = P_m - P_e \tag{12}$$

$$\frac{dE'_q}{dt} = \frac{1}{T'_{do}}[E_{fd} - E'_q - (x_d - x'_d)i_d] \tag{13}$$

$$\frac{dE'_d}{dt} = \frac{1}{T'_{qo}}[-E'_d + (x_q - x'_q)i_q] \tag{14}$$

Here, the subscripts *d*, *q* and *f* refer to armature direct, quadrature axes and field quantities, respectively. The superscript $'$ denotes transient quantities. δ is the rotor angle for each machine with respect to the reference machine. *M* and *D* are inertia and damping constants. *E*, *i*, *x*, *T* represent the voltages, currents, reactances and time constant, respectively.

Eqn. 12 is the familiar electromechanical swing eqns. and 13 and 14 are the quadrature and direct axes flux linkage equations, respectively. The IEEE type-1 exciter model used for this study is given in Fig. 11.

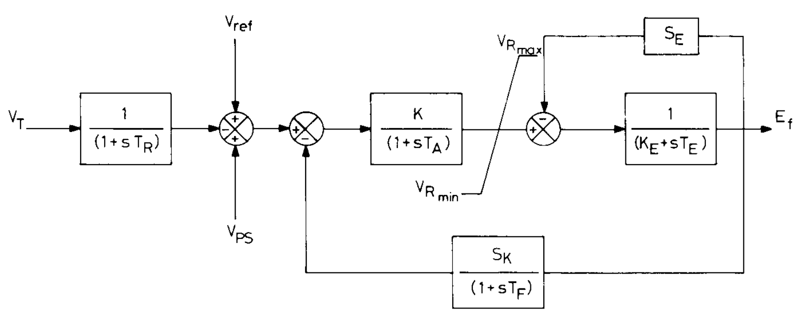

Fig. 11 *IEEE type 1 excitation system*