Dynamic Braking Resistor for Control of Sub-synchronous Resonant Modes

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Abstract: A dynamic braking resistor control strategy has been proposed to damp the slowly growing sub-synchronous resonant frequency oscillations. It employs generator speed variation, rotor angle and power variation signals to switch in braking resistors at the generator terminal. The proposed control has been tested on the IEEE second benchmark model for sub-synchronous resonance studies. The dynamically switched braking resistors have been found to control the unstable modes very effectively. The control algorithm is simple and its realization will require very little hardware.

Keywords: Damping Control, SSR, Series Capacitor Compensation, Dynamic Brake.

I. INTRODUCTION

Investigations in sub-synchronous resonance (SSR) phenomena continue to be a subject of intense interest as can be seen from the large number of publications included in bibliography compiled by the IEEE Working Group on SSR [1-3]. Depending on the extent of compensation, series capacitor compensated lines may have natural modes of oscillations, which are weakly or even negatively damped. A system with such natural modes of oscillation will respond more actively to inputs that contain frequencies near to these natural modes. Although a generator shaft is sufficiently damped so as to prevent steady state oscillation, the damping factors may be small enough such that damaging shaft torques can be created by a particular disturbance. Measures proposed in the literature for countering this type of oscillation arising at smaller frequencies are excitation control, static var compensators, HVDC, static phase shifter, bypass filter and shunt reactors [4-8].

The use of resistive brake to damp the oscillations seen in the mechanical mass-spring system of a turbine shaft was reported in [9,10]. The resistor switching was primarily done depending on machine speed changes. Since the nature of the low frequency oscillations is different from transient instability situation, a search for other possible or more appropriate stabilizing signals should be carried out. Also the power ratings of the brakes for such slowly growing oscillations would be different from transient stability situations.

This paper proposes a dynamic braking resistor switching strategy for control of unstable SSR modes. The control is derived as an optimal combination of speed deviation and accelerating power of the generator. The strategy has been tested on the IEEE second benchmark model and found to be very effective in controlling the SSR oscillations. The power requirement of the brake is significantly small.

II. SECOND BENCHMARK MODEL WITH DYNAMIC BRAKE

The IEEE second benchmark model for SSR studies [5,11] shown in Fig.1 is considered for this study. The system consists of a synchronous generator feeding an infinite bus over two parallel transmission lines, one of which is capacitor compensated. The mechanical part of the generating unit is a mass-spring system containing four masses shown in Fig.2. The high-pressure turbine (HP), the low-pressure turbine (LP), the generator (GEN), and the exciter (EX) are all coupled on the same shaft.

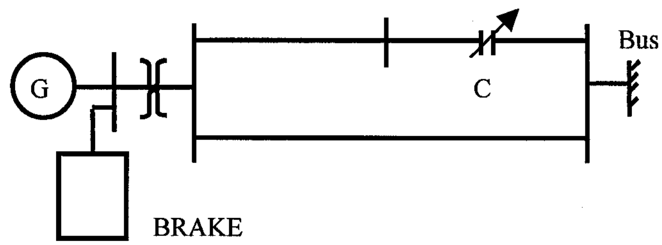

Fig.1. Configuration of the IEEE second bench -mark model with SMES.

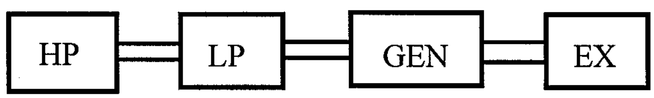

Fig.2. The generator turbine system.

The dynamic resistor brake is connected to the system at the generator terminals. The IEEE Type 1 exciter is included to represent the excitation system of the second benchmark model.

The dynamic model of the system given in Fig.1 comprising of the electromechanical swing equation of the generator, the voltage-current-flux relationships of its various circuits, the excitation system, the transmission line containing the series capacitor, and the mass-spring system on the generator shaft can be written in the form

$$\dot{X} = f[X,u] \qquad (1)$$

where, the state vector X is

$$X = [X_1\ X_2\ X_3\ X_4]^T \qquad (2)$$

$$X_1=[\omega_H, \theta_H, \omega_L, \theta_L, \omega, \delta, \omega_E, \theta_E]$$

$$X_2=[i_d, i_f, i_D, i_q, i_Q, i_S]$$

$$X_3=[e_{cd}, e_{cq}, i_{cd}, i_{cq}]$$

$$X_4=[V_A, E_{fd}, V_S]$$

Control **u** is the brake output power P_b

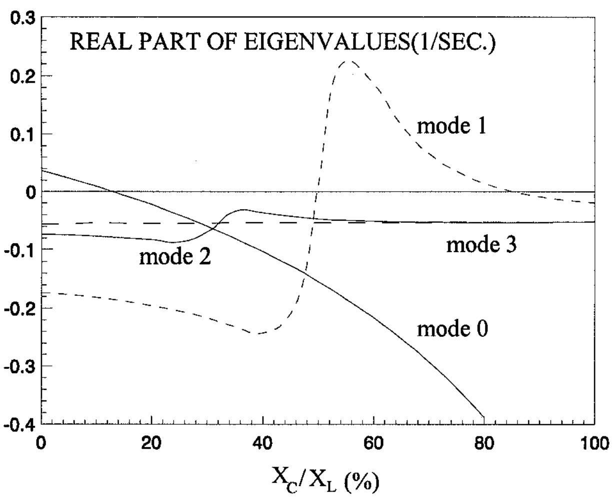

Fig. 3 The real part of the eigenvalues of the sub-synchronous modes for various degrees of compensation.

For small perturbations of the states, the system of equation (1) can be linearized around the steady state equilibrium point and expressed as,

$$\Delta\dot{X} = A\,\Delta X + B\,u \qquad (3)$$

where, ΔX is the change of the state vector. The matrix A in the above equation depends on the degree of series capacitor compensation. The compensation factor, given as X_C/X_L, is normally expressed in percent. The real parts of the eigenvalues of the sub-synchronous modes for various values of compensation factors are plotted in Fig. 3. The eigenvalue corresponding to the electromechanical swing is termed mode 0, while the other sub-synchronous modes in ascending order are termed modes 1, 2, and 3. Fig. 3 shows that at lower values of compensation the electromechanical mode (mode 0) is unstable. This is expected for a weakly connected power system. With the increase in compensation, the real part of the electromechanical mode starts to decrease, while that of mode 1 starts to increase. At 56% capacitor compensation, mode 1 has the largest real part. The variations of the imaginary parts of the modes are not significant.

III. THE PROPOSED BRAKE CONTROL STRATEGY

Braking resistors are known to help stabilize a power system under transient conditions by absorbing the excess energy of the system following three-phase faults or other severe disturbances. The damping characteristics of power systems that are prone to SSR conditions can also be improved with dynamic braking resistor. The brakes can be switched in to the network when the generator accelerates, triggered by inputs having supplement of the SSR mode. The following analysis presents a switching algorithm for the braking resistors that will restore the system to normal operating condition in minimum possible time.

Consider the electromechanical swing equation of the generator included in the general dynamic equation (1) for the single machine system. This is rewritten as

$$M\,p^2\delta = P_m - P_e - P_b \qquad (4)$$

where, p is the derivative operator d/dt. P_m, P_e are the mechanical power input and electrical power output of the generator, respectively. The equation can be rewritten as

$$p^2\delta = b\,\Delta P + b\,u \qquad (5)$$

Here, b is the reciprocal of inertia constant. Contro u which is the power absorbed by the brake, can vary from 0 to a maximum, say 1; hence the constraint on the control variable can be written as

$$0 \le u \le 1 \qquad (6)$$

Since one of the main objectives in stabilizing the power system is to bring the states back to their equilibrium values quickly, this can be formulated as an optimization problem minimizing the cost index

$$J = \int_{t_0}^{t_f} dt \qquad (7)$$

A quasi-optimum control strategy for the problem stated above can be written as

$$u = \begin{cases} 1 & (\textit{braking resistor on})\ \text{if}\ \Sigma \ge 0 \\ 0 & (\textit{braking resistor off})\ \text{if}\ \Sigma < 0 \end{cases} \qquad (8)$$

where,

$$\Sigma = \delta - \frac{p\delta^2}{2[b.\Delta P - b.\mathrm{sgn}\{p\delta\}]} \qquad (9)$$

Normally, the target value for δ may not be the original operating point; rather it may be the stable manifold of 0 to π/2. Equation (9) in that case will be modified accordingly.

The relations (8) and (9) show that if the rotor angle has to be restored to the original value following a disturbance, the brake switching depends on the weighted value δ and pδ, the weight depending on the power unbalance ΔP of the generator. However, if there is no constraint on δ, the braking strategy depends on the speed variation of the generator alone.

IV. SIMULATION RESULTS

The IEEE second benchmark model for SSR studies with one generating unit and two parallel transmission lines and a dynamic resistor brake unit connected to the generator bus, as given in Fig. 1, was simulated. The system of equation (1) was solved without and with the proposed braking control scheme. 56% series capacitor compensation of one of the transmission lines which gives the largest real part of SSR mode 1 was considered. A torque pulse of 20% for duration of 3 cycles was applied to the generator shaft. Figure 4 shows the response in the absence of any control. The response is slowly growing. The torque on the shaft of the various sections of the turbine as well the generator is oscillatory and growing. Amongst all the three torsional torques, the high pressure and low-pressure section, the low pressure and generator, and the generator and exciter, the LP-GEN torque is the largest. The top plot in Fig. 4 shows the variation of this torsional torque. The variations of angular frequency and the terminal voltage are also shown in the same figure. Fig. 5 shows the variation of the respective quantities when the proposed brake control is applied. The maximum amount of brake power applied for the response shown in Fig. 5 is 10%. The variation of P_b as determined by the optimum strategy is shown in Fig.6. Examination of Figs. 5 and 6 indicate that the small frequency oscillations have been completely captured in about 1 second.

The optimum strategy (8) gives the output power as a bang-bang function. Realization of this type of discrete control is, generally, difficult because of instrumentation time lags. In this simulation a control u=KΣ was used instead. K was selected by trial and error so that the control reaches the ceiling value when the oscillations are relatively large. Also, a dead-zone was provided to minimize unnecessary use of brake power when the oscillations have sufficiently died down.

The effectiveness of the brake control strategy was examined with various amounts of maximum brake power. It was observed that the unstable modes could be controlled with a maximum brake power of as low as 2% for this disturbance condition. Expectedly, the oscillations take a little longer while to stabilize as can be seen in Fig. 7.

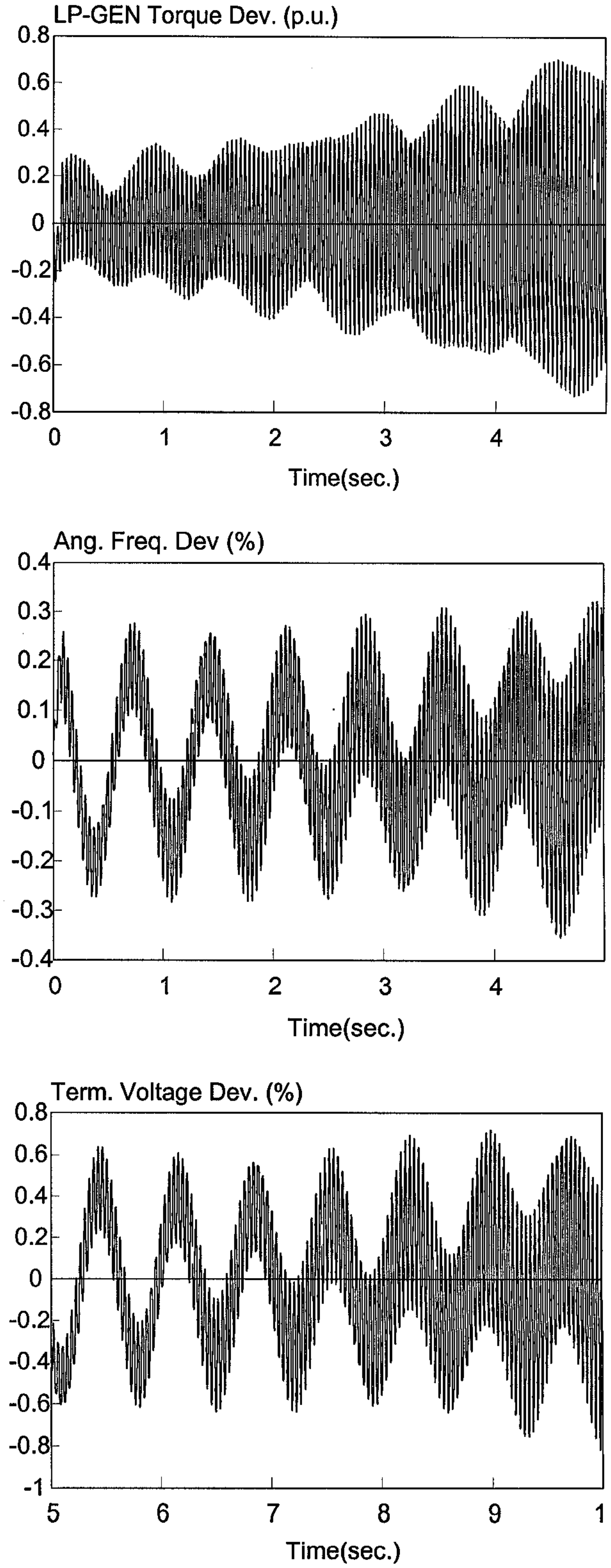

Fig. 4 Variation of LP-GEN torsional torque, generator angular speed and terminal voltage variation following a 20% torque pulse on the generator shaft for 3 cycles without any stabilizing control.

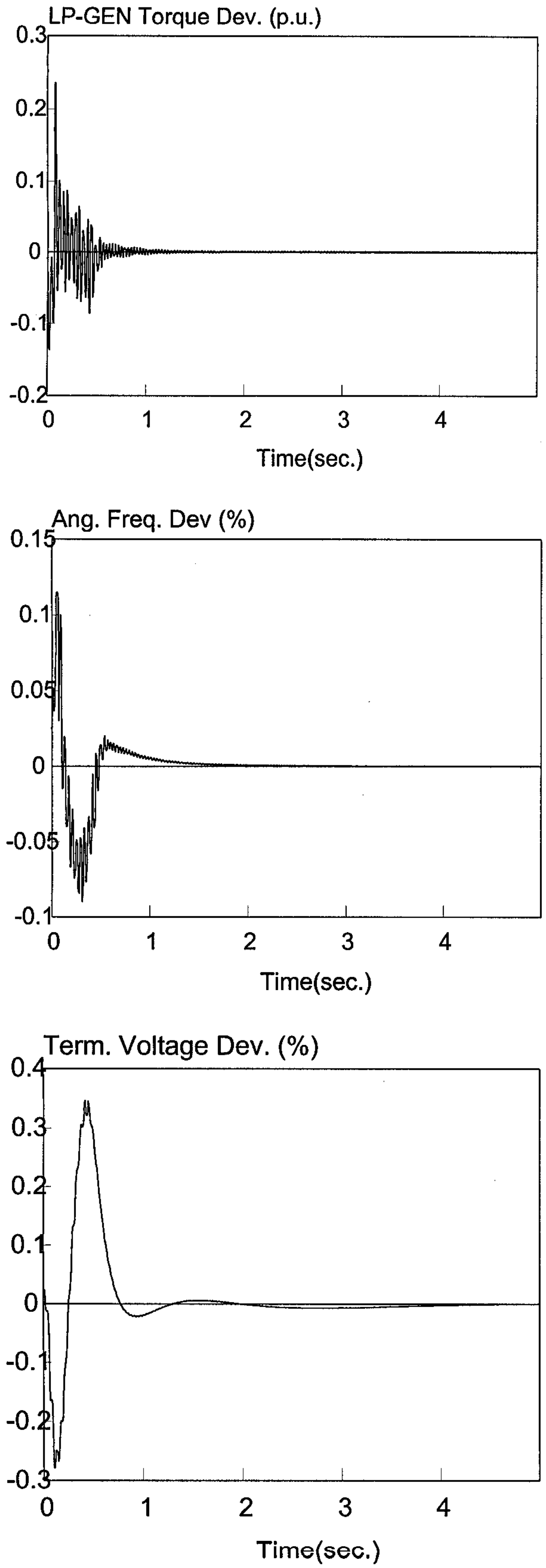

Fig. 5 Variation of LP-GEN torque, generator angular speed and terminal voltage corresponding to Fig. 4 with the proposed dynamic braking control.

The SSR behavior of the system was examined with a severe disturbance of a symmetrical three-phase fault on the generator bus for 3 cycles. The angular speed and terminal voltage variations of the generator with a maximum brake power of 50% is shown in Figs. 8 and 9. Fig. 10 shows the variation of the brake power output as a function of time. Fig. 11 shows that with as little as 5% maximum brake powers the SSR oscillations for this severe fault conditions can be controlled. The number of switching in that case is more than the condition shown in Fig. 10.

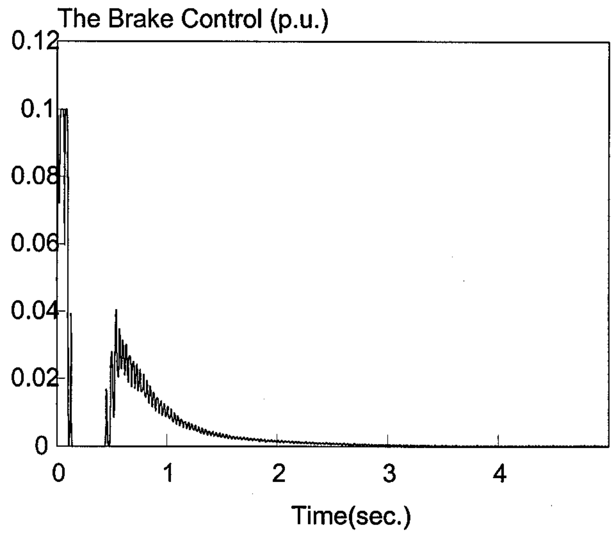

Fig. 6 The variation of brake power P_b corresponding to Fig.5.

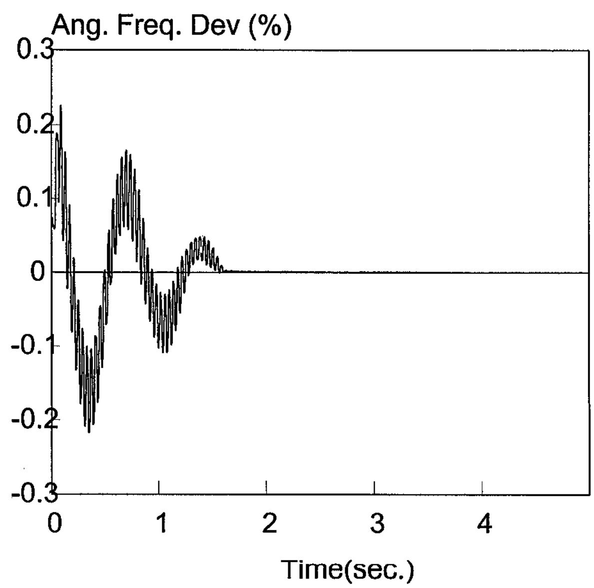

Fig. 7 Generator angular speed variation for a 20% torque pulse disturbance with a maximum brake power of only 0.02 pu.

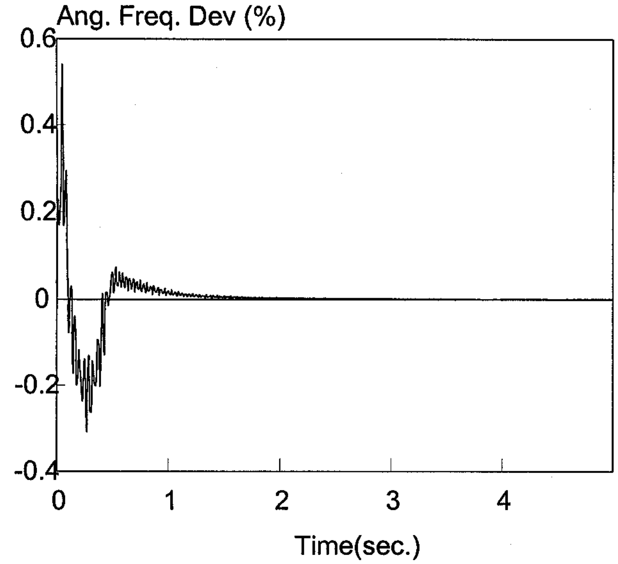

Fig. 8 Generator angular speed variation following a three-phase fault for 3 cycles at the generator terminal with a maximum brake power of 0.5pu.

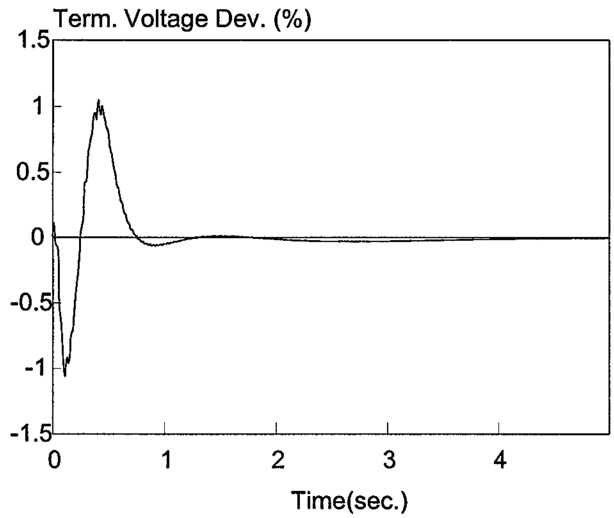

Fig. 9 Terminal voltage variation following a three-phase fault for 3 cycles with a maximum brake power of 0.5pu.

V. CONCLUSIONS

A method of controlling the sub-synchronous resonant oscillations through the control of dynamic braking resistors connected to the generator bus is presented. The control strategy is formulated such that the generator speed and rotor angle are brought back to the desired steady conditions in shortest possible time.

Transient response recorded show that the sub-synchronous frequency oscillations are eliminated quickly with judicious use of brake power. It has been observed that even for a severe three-phase fault condition, the SSR oscillations can be controlled with a maximum brake output power of as low as 0.05 pu. This is quite different from the transient stability conditions where brake power requirement of 1.0 pu or more is not unusual. If dynamic brakes are installed to cater for both transient stability as well as SSR type oscillations, circuits should be designed properly to minimize brake control power.

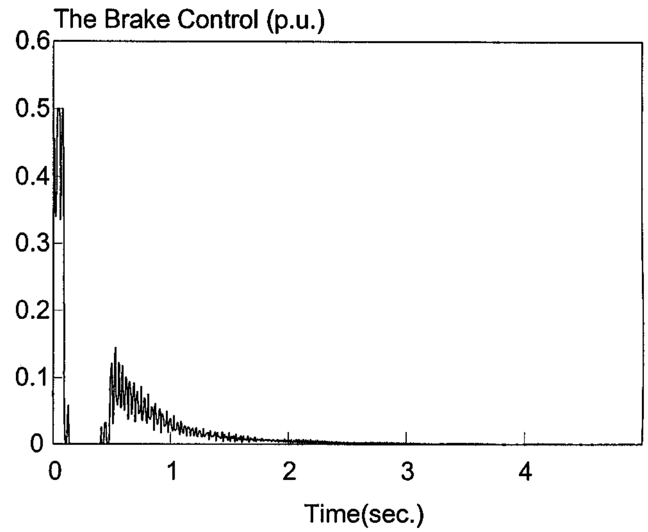

Fig. 10 The variation of brake power P_b corresponding to Fig.7.

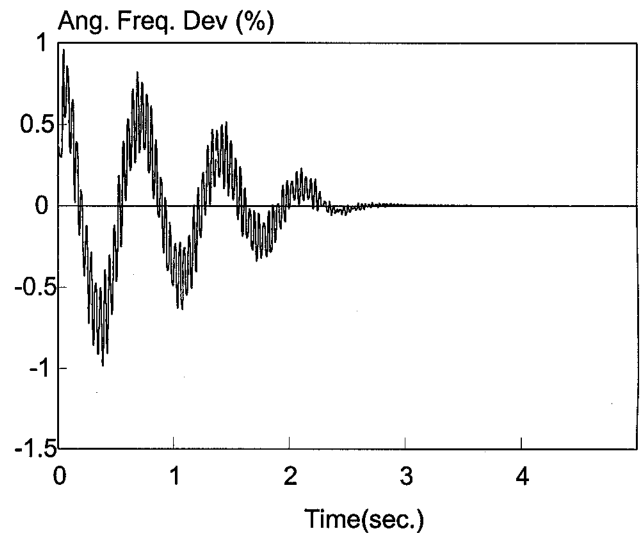

Fig. 11 Generator angular speed variation following a three-phase fault for 3 cycles at the generator terminal with a maximum brake power of only 0.05pu.

In actual implementation, the braking control strategy proposed requires primarily the measurement of the changes in generator speed, rotor angle and its power output. The proposed strategy is simple and would require very little hardware to implement.

VI. ACKNOWLWEDGEMENTS

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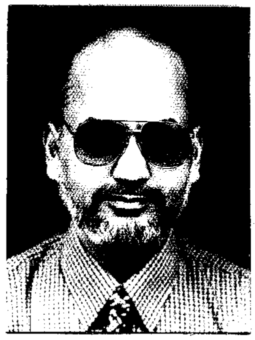
VIII. BIOGRAPHIES



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