A Robust STATCOM Controller for Power System Dynamic Performance Enhancement

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Abstract: A robust controller for providing damping to power system transients through STATCOM devices is presented. Method of multiplicative uncertainty has been employed to model the variations of the operating points in the system. The design is carried out applying robustness criteria for stability and performance. A loop-shaping method has been employed to select a suitable open-loop transfer function, from which the robust controller is constructed. The proposed controller has been tested through a number of disturbances including three-phase faults. The robust controller designed has been demonstrated to provide extremely good damping characteristics over a good range of operating conditions.

Keywords: STATCOM, FACTS devices, robust control, damping control, loop-shaping method.

1.INTRODUCTION

It is well established that reactive compensation of transmission lines through rapidly variable solid state, thyristor switches of the FACTS devices improve both the transient as well as dynamic performances of a power system [1]. These devices dynamically control the power flow through a variable reactive admittance to the transmission network and, therefore, generally change the system admittance. Controllable synchronous voltage sources, known as static compensators, are a recent introduction in power systems for dynamic compensation and for real time control of power flow. The static compensator (STATCOM) provides shunt compensation in a similar way to the static var compensators (SVC) but utilizes a voltage source converter rather shunt capacitors and reactors [2]. The basic principle of operation of a STATCOM is the generation of a controllable AC voltage source behind a transformer leakage reactance by a voltage source converter connected to a DC capacitor. The voltage difference across the reactance produces active and reactive power exchanges between the STATCOM and the power system [3]. It has been reported that STATCOM can offer a number of performance advantages for reactive power control applications over the conventional approaches because of its greater reactive current output capability at depressed voltage, faster response, better control stability, lower harmonics, and smaller size, etc. [4].

Two basic controls are implemented in a STATCOM. The first is the AC voltage regulation of the power system, which is realized by controlling the reactive power interchange between the STATCOM and the power system. The other is the control of the DC voltage across the capacitor through which the active power injection from the STATCOM to the power system is controlled [3,5]. The STATCOM is normally designed to provide fast voltage control and to enhance damping of inter-area oscillations. A typical method to meet these requirements is to superimpose a supplementary damping controller upon the automatic voltage control loop [4].

The effect of stabilizing controls on STATCOM controllers have been investigated in several recent reporting [3-6]. PI controllers have been found to provide stabilizing controls when the AC and DC regulators were designed independently. However, joint operations of the two have been reported to lead to system instability because of the interaction of the two controllers [3,6]. While superimposing the damping controller on the AC regulator can circumvent the negative interaction problem, the fixed parameter PI controllers have been found invalid, or even to provide negative damping for certain system parameters and loading conditions [4].

This article investigates the effect of a damping controller in the voltage regulator loop of the STATCOM. A robust controller is designed for a single machine infinite bus system with a STATCOM. The variations of the operating conditions have been taken into consideration by modeling them as multiplicative unstructured uncertainty. A loop-shaping technique [7] has been employed to design the controllers. Two robust controllers, one in the speed feedback and the other in the voltage feedback loop have been investigated. It was observed that a robust controller in the speed loop with a nominal voltage feedback effectively damps the electromechanical oscillations, and keeps the bus voltage variations to significantly small levels, for a wide range of operating conditions.

2. THE POWER SYSTEM MODEL

A single machine infinite bus system with a STATCOM connected through a step–down transformer is shown in Fig.1. The robust controller is designed considering a worst-case dynamic model with the following assumptions [4].

a. No detailed exciter and governor dynamic models; constant generator voltage e_q' behind reactance x_d'; damping is neglected; mechanical power input P_m is constant.

b. STATCOM is a reactive current source with time delay. Inductive current generated by STATCOM is assumed positive.

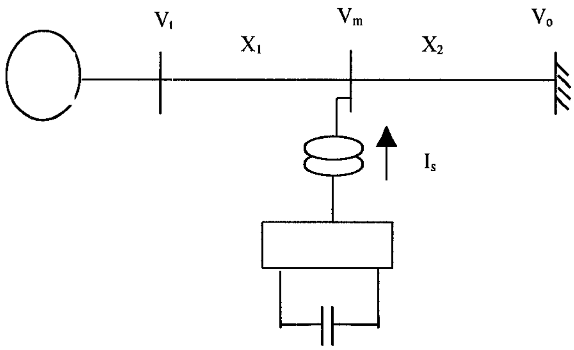

Fig.1 Single Machine System with STATCOM

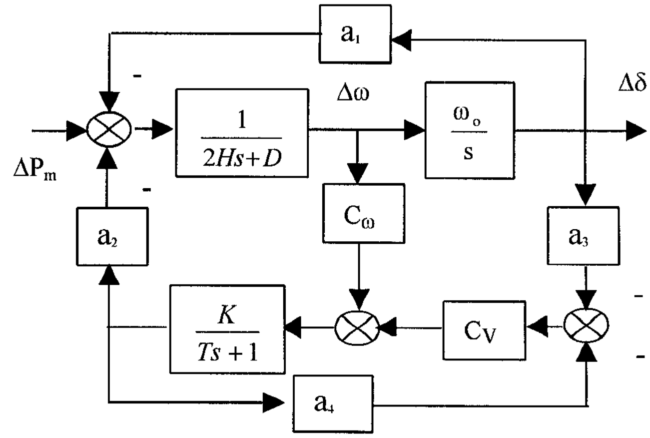

Fig.2 Block diagram of the linearized system.

The system is then described by the following equations:

$$
\begin{aligned}
\Delta\dot{\delta} &= \omega_0 \Delta\omega \\
\Delta\dot{\omega} &= \frac{1}{2H}[D\Delta\omega - \Delta P_e] \\
\Delta\dot{I}_S &= \frac{K}{T}[-\Delta I_S + C\Delta u]
\end{aligned}
\qquad (1)
$$

where, δ is the load angle,ω is the angular speed, 2H is the inertia constant, D is the damping constant. The delivered electrical power P_e is expressed as

$$P_e = \frac{e_q' V_m}{x_d' + x_1}\sin\theta + \frac{V_m^2}{2}\frac{x_d' - x_q}{(x_d' + x_1)(x_q + x_1)}\sin 2\theta \qquad (2)$$

The direct and quadrature axes components of bus voltage V_m are written as

$$V_{mq} = \frac{(x_1 + x_d')V_o \cos\delta + e_q' x_2 + I_S x_2 (x_1 + x_d')\cos\theta}{x_1 + x_2 + x_d'} \qquad (3)$$

$$V_{md} = \frac{(x_1 + x_q)V_o \sin\delta + I_S x_2 (x_1 + x_q)\sin\theta}{x_1 + x_2 + x_q} \qquad (4)$$

θ is the phase difference between quadrature axis of the generator and V_m, and is related as, $\tan\theta = V_{md}/V_{mq}$.

By linearizing equations (2),(3), and (4), the variations in power output and STATCOM bus voltages are written as

$$
\begin{aligned}
\Delta P_e &= a_1 \Delta\delta + a_2 \Delta I_S \\
\Delta V_m &= a_3 \Delta\delta + a_4 \Delta I_S'
\end{aligned}
\qquad (5)
$$

where, $a_1 = \partial P_e/\partial\delta$, $a_2 == \partial P_e/\partial I_s$, $a_3 == \partial Vm/\partial\delta$, and $a_4 = \partial V_m/\partial I_S$.

The STATCOM controller output is written as,

$$\Delta u = -C_V\ \Delta Vm + C_\omega \Delta\omega \qquad (6)$$

C_v and C_ω are the controllers in the voltage and speed loop, respectively. The linearized system block diagram is given in Fig.2.

3. ROBUST CONTROL DESIGN

A robust STATCOM controller is designed for a range of operating points by considering perturbations around a nominal plant. These perturbations are modeled as multiplicative uncertainties in the robust design procedure. This section gives a brief theory of the uncertainty model, the robust stability criterion, a graphical design technique termed loop shaping, which is employed to design the robust controller. Finally, the algorithm for the control design is presented.

3.1 Uncertainty Modeling

Suppose that the nominal plant transfer function of a plant is P and consider that the perturbed transfer function because of variations of parameters a_1, a_2, a_3, a_4 in Fig.2 (for various operating conditions) can be expressed in the form

$$\tilde{P} = (1 + DW_2)P \qquad (7)$$

Here, W_2 is a fixed stable transfer function, the weight, and D is a variable transfer function satisfying $\|D\|_\infty < 1$. In the multiplicative uncertainty model (7), DW_2 is the normalized plant perturbation away from 1. If $\|D\|_\infty < 1$, then

$$\left|\frac{\tilde{P}(j\omega)}{P(jw)} - 1\right| \le |W_2(j\omega)|, \forall\omega \qquad (8)$$

So, $|W_2(j\omega)|$ provides the uncertainty profile and in the frequency plane is the upper boundary of all the normalized plant transfer functions away from 1.

3.2 Robust Stability and Performance

Consider a multi-input control system given in Fig.3. Suppose that the plant transfer function P belongs to a set P. A controller C provides robust stability iff it provides internal stability for every plant in the set P.

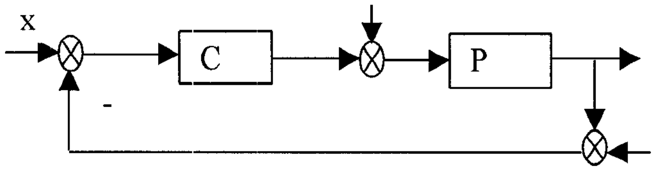

Fig.3 Unity feedback plant with controller.

Theorems: C provides robust stability iff $\|W_2T\|_\infty < 1$, *for multiplicative uncertainty. Also, necessary and sufficient condition for robust performance is* $\| |W_1S| + |W_2T| \|_\infty < 1$. *The nominal performance condition is given as* $\|W_1S\|_\infty < 1$ [7].

In the above, W_1 is a real, rational, stable and minimum phase function. T is the input-output transfer function, complement of the sensitivity function S, and is given as

$$T = 1 - S = \frac{1}{1+L} = \frac{1}{1+PC} \quad (9)$$

The proofs of the above theorems are given in reference [7].

3.3 The Loop Shaping Technique

Loop shaping is a graphical procedure to design a proper controller C satisfying robust stability and performance criteria given in sec.3.2. The basic idea of the method is to construct the loop transfer function, L=PC to satisfy the robust performance criterion approximately, and then to obtain the controller from the relationship C=L/P. Internal stability of the plants and properness of C constitute the constraints of the method. Condition on L is such that PC should not have any pole zero cancellation. A necessary condition for robustness is that either or both $|W_1|, |W_2|$ must be less than 1[8]. If we select a monotonically decreasing W_1 satisfying the other constraints on it, it can be shown that at low frequency the open-loop transfer function L should satisfy,

$$|L| > \frac{|W_1|}{1-|W_2|} \quad (10)$$

while, for high frequency,

$$|L| < \frac{1-|W_1|}{|W_2|} \approx \frac{1}{|W_2|} \quad (11)$$

At high frequency $|L|$ should roll-off at least as quickly as $|P|$ does. This ensures properness of C. The general features of open loop transfer function is that the gain at low frequency should be large enough, and $|L|$ should not drop-off too quickly near the crossover frequency to avoid internal instability.

3.4 The Algorithm

The control design procedure for robust stability and robust performance can be summarized in the following steps.

1. Obtain the db-magnitude plot for the nominal as well as perturbed plant transfer functions.
2. Construct W_2 satisfying constraint (8).
3. Select W_1 as a monotonically decreasing, real, rational and stable function.
4. Choose L such that it satisfies conditions (10) and (11). The transition at crossover frequency should not be at a slope steeper than –20db/decade.
5. Check for the nominal and robust performance criteria given in the theorems in section 3.2.
6. Test for internal stability by direct simulation of the closed loop transfer function for pre-selected disturbances or inputs.
7. Repeat steps 4 through 6 until satisfactory L and C are obtained. Note that a robust controller may not exist for all nominal conditions, and if it does, it may not be unique.

4. IMPLEMENTATION

As shown in Fig.2, the STATCON can be controlled through two control functions C_ω and C_V in the speed and voltage feedback loops, respectively. In this study, the robust damping control design was carried out independently for each loop. The effect of employing control in both the loops simultaneously was then investigated.

4.1 Robust Speed Controller Design

The robust controller design procedure starts by arranging the system in the form as shown in Fig.3. The block diagram of the system without considering the voltage feedback, and in the absence of any input is shown in Fig.4.

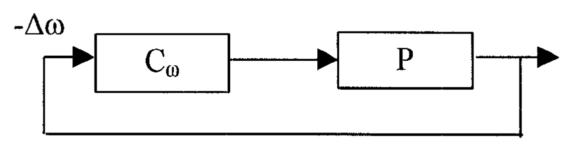

Fig 4 Collapsed block diagram for robust speed feedback system.

The nominal operating point for the design was computed for delivered power of 0.8 per unit at unity power factor. Off-nominal power outputs between 0.2-1.2 p.u and power factors ranging between 0.8 lag –0.8 lead were considered. The power system data is given in the Appendix. The db-magnitude vs. frequency response for the nominal and perturbed plants is plotted in Fig.5. The nominal plant transfer function for the selected operating point is computed as

$$P = \frac{1.0435s}{(s+50)(s^2+60.66)} \quad (12)$$

From Fig.5, the quantity $|\tilde{P}(j\omega)/P(j\omega)-1|$ for each perturbed plant is constructed and the uncertainty profile is fitted to the function

$$W_2(s) = \frac{0.8s^2+2.24s+39.2}{s^2+0.98s+49} \quad (13)$$

A Butterworth filter satisfies all the properties for $W_1(s)$ and is written as,

$$W_1(s) = \frac{K_d f_c^2}{s^3 + 2s^2 f_c + 2s f_c^2 + f_c^3} \quad (14)$$

For K_d=1 and f_c=0.1 in W_1 and for a choice of the open loop transfer function L as,

$$L(s) = \frac{208.75(s+1)(s+2)}{(s+.01)(s+50)(s^2+60.66)} \quad (15)$$

gives the desired controller transfer function,

$$C_\omega(s) = \frac{200(s+1)(s+2)}{s(s+.01)} \quad (16)$$

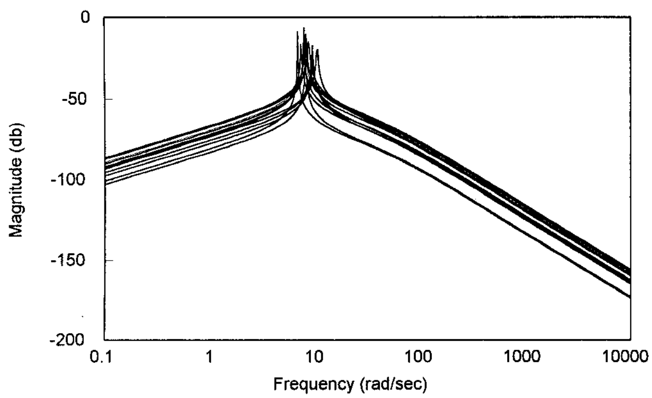

Fig.5 Nominal and perturbed plant transfer functions.

The db-magnitude plot relating W_1, W_2 and L, which was employed to arrive at the controller, is shown in Fig. 6. The plots for the nominal performance and robust performance criteria are shown in Fig.7. Notice that nominal performance criterion has been very much satisfied, while the robust performance criterion exceeds 1 for a very small frequency range. This peaking in frequency is for the worst-case design of the controller for damping D=0. Though, in reality, some damping is present, the procedure shows that the performance criterion may not be satisfied for all possible conditions. This is, of course, expected in the power system problem.

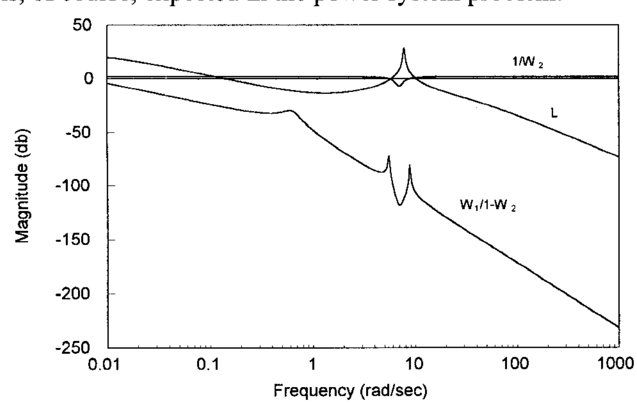

Fig. 6 Loop shaping plots relating W_1, W_2 and L.

The robust STATCON speed controller was tested by applying an input torque pulse of 100% of 0.05 sec. duration to the generator shaft. The speed variation of the generator for the nominal operating condition is shown in Fig.8. The rotor angle variations for a number of operating conditions are plotted in Fig. 9.

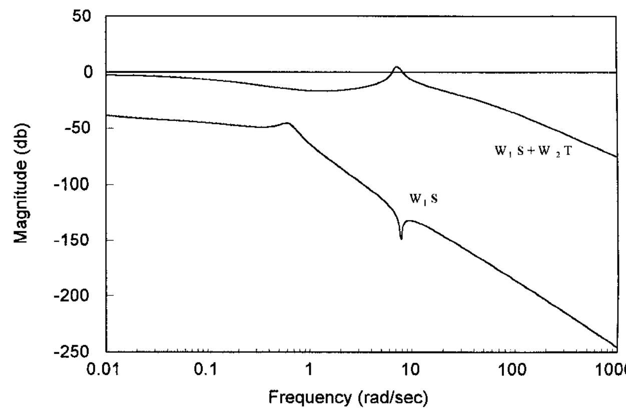

Fig.7 Robust and nominal performance criteria.

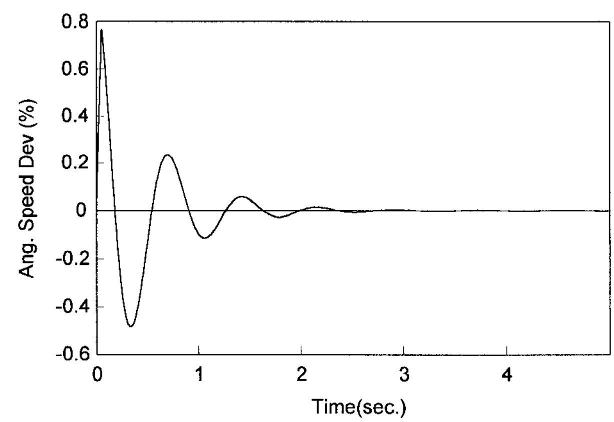

Fig.8 Generator speed variation of with robust controller in the speed loop.

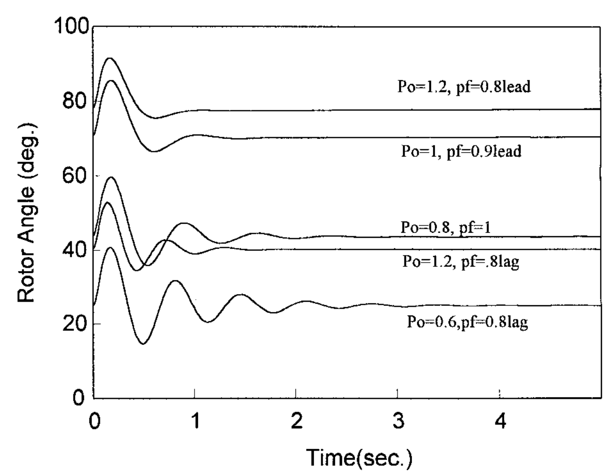

Fig.9 Load angle with the robust controller for various conditions.

It can be observed that good damping properties can be obtained with the robust speed controller over a wide range of operating conditions. While, the controller can be designed to provide still more damping, the steady state error and peak overshoot in the bus voltages may be excessive in this case

4.2 Robust Controller Design in the Voltage Loop

The block diagram corresponding to Fig. 4 with the voltage loop controller is shown in Fig.10.

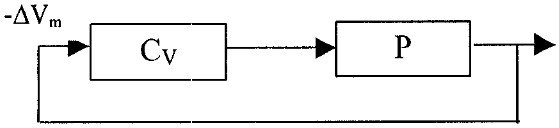

Fig.10 Collapsed block diagram with voltage controller.

The nominal plant transfer function for this formulation is

$$P = \frac{-10.31885(s^2+65.505)}{(s+50)(s^2+60.7316)} \tag{17}$$

Because of the sign of P, the nominal plant is in a positive feedback loop. Such a system does not fall in the category of internal stability [7] and robustness criterion cannot be applied as such. However, by forcing C_V to take the opposite polarity, a robust controller was designed following similar procedure as in sec. 4.1. The controller does provide reasonable amount of damping over a range of operating conditions, but is not as effective as the speed controller C_ω. It is to be noted that earlier studies also revealed that the STATCON voltage control loop does not provide enough damping [4,6]. PI controller design is often unsatisfactory, and may even lead to unstable situations [6]. This can be attributed to the fact that there is a pair of poles and a pair of zeroes in P on the imaginary axis, which are in close proximity. These pole-zero pairs are responsible for the oscillatory nature of response in that voltage loop which is a desirable for voltage regulation purpose. In the following section, a robust design for a controller in the speed loop is presented which retains a nominal voltage feedback $C_V = 1$.

4.3 Coordinated Robust Speed Controller

The nominal plant transfer with robust controller in the speed loop and including the voltage feedback can be expressed as,

$$P(s) = \frac{1.043s^2}{(s+58.6249)(s^2+1.694s+10.69)} \tag{18}$$

Note the positive feedback situation disappears allowing a proper robust design. Continuing with the same design procedure employed in sec. 4.1, a choice of the open loop transfer function,

$$L(s) = \frac{104.35(s+7)(s^2+2s+1)}{(s+.01)(s+58.6249)(s^2+5s+49)} \tag{19}$$

with the resulting control function,

$$C(s) = \frac{100(s+7)(s^2+2s+1)(s^2+1.694s+10.69)}{s^2(s+.01)(s^2+5s+49)} \tag{20}$$

provides excellent damping control over a wide range of operating conditions. The load angle and bus voltage variations for 5 widely varying loading conditions are shown in Figs. 11 and 12, respectively. As can be observed, the robust controller provides very good overall damping characteristics. All these case studies are for a 100% input torque pulse for 0.05 sec. duration.

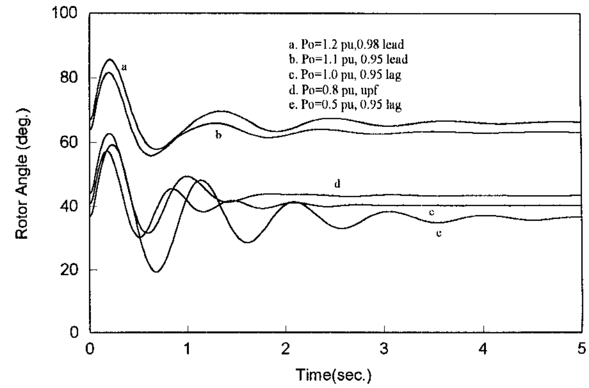

Fig.11 Generator power angle for various loading conditions

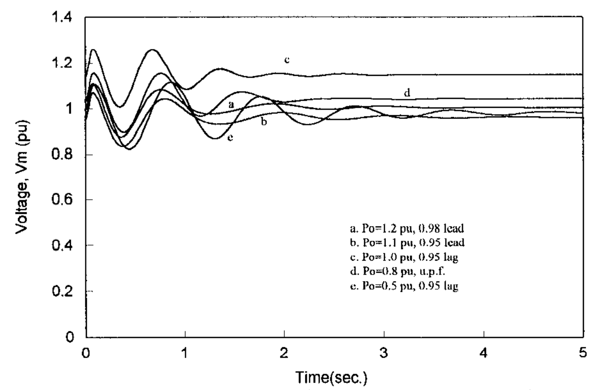

Fig.12. Bus voltage variations for various loading conditions.

4.4 Fault Studies

The coordinated robust controller designed through the linear system modeling was then applied to the nonlinear power system model. The set of nonlinear equations (2), (3), and (4) were employed to solve the power output and bus voltage of the STATCON. Note that these nonlinear equations have to solved at each integration step iteratively. For a self-clearing three-phase fault for 0.1second on the remote bus, the generator torque and bus voltage are shown in Figs. 13 and 14, respectively. Two loading conditions are considered - (a) nominal power output of 0.8pu at 0.99 leading power factor, (b) steady state pre-fault output of 1.1pu at 0.95 lagging power factor. The transient profile of load angle and bus voltage, with fault on the overloaded machine, show that the control design is extremely robust.

5. CONCLUSIONS

A novel method of designing robust damping control strategies for STATCON controller in a power system is proposed. The controller designed was tested for a number of disturbance conditions including symmetrical three-phase faults. The robust design has been found to be very effective for a range of operating conditions of the power system. The operating conditions for which the controller provides good performance depends on the spectrum of perturbed plants selected in the design process. The robust design is much superior to the conventional PI and similar other controllers, where the controller coefficients normally need to be retuned for various operating conditions. The graphical loop-shaping method is simple and straightforward to implement.

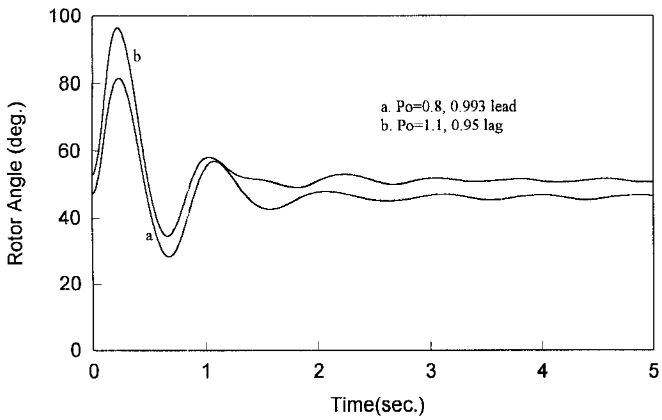

Fig.13 Generator angle variations following fault for 2 different operating conditions.

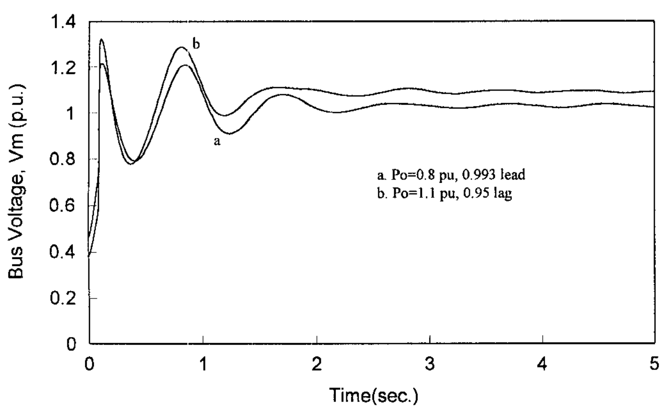

Fig.14 Terminal voltage characteristics corresponding to Fig.15.

6. ACKNOWLEDGEMENT

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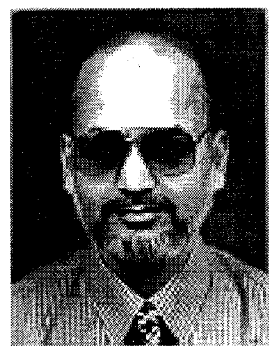
8.APPENDIX

The power system data are as follows:
$H=3$ sec., $D=0$, $x_l=0.3$, $x_2=0.3$, $x_d'=0.3$, $x_d=1.0$, $x_q=0.6$, $K=1$, $T=0.02$, $I_{so}=0$.



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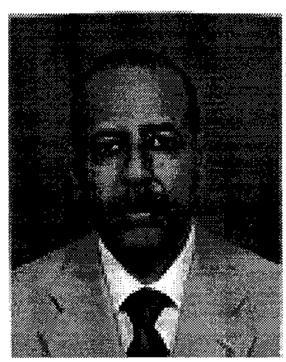

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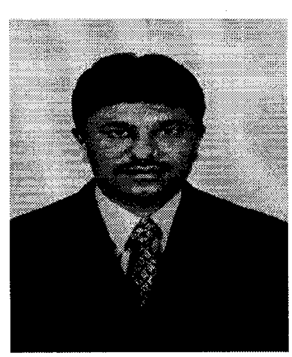

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