DESIGN OF MULTIVARIABLE NONLINEAR FEEDBACK CONTROL SYSTEM OF POWER SYSTEM

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Abstract

A power system is a large-scale, nonlinear, and multivariable system having groups of generators, buses and branches. Linearization of this nonlinear multivariable system is carried out around an operating point. The linear regulator has disadvantages that it is generally not valid for large disturbances and that a large amount of computations and information transmission are necessary for reconstructing linearized model at each operating point. The proposed method aims at solving the difficulties and realizing the design of the multivariable feedback control system. A nonlinear approximate model is constructed which retains nonlinearity of the controlled power system dynamics which retains the interactions between the state variables, etc. A nonlinear-regulator is designed for the model which determines suboptimal policy under a specific cost function. The primary purpose of the proposed method is to establish a governor and exciter control system which is adaptable to the large disturbances and the changes of operating points, and successful results are obtained.

INTRODUCTION

The control of power systems consisting of interconnected networks of transmission lines linking generators and loads is an important problem since the power system is a large scale non-linear multivariable system. Traditionally, the problem of design of power systems is split into two separate problems. For simplicity, the design of excitation-control systms and governor-control systems are carried out independently. Excitation controllers are designed assuming constant mechanical torque input for the regulation of terminal voltage and improving generators stability limit, and the governor control system is designed assuming constant flux linkage for power frequency regulation [1,3]. An integrated excitation and governor controller design based on the complete model is more effective in improving the performance of a power system. However, increased order and nonlinearity pose difficulties in designing an integrated controller.

Problems arise from how to formulate the physical phenomena and solve the nonlinear multivariable problems. In dealing with the kinds of problems, linearization is carried out around an operating point and problem oriented aggregation is performed to construct a linear low order model. A desired control is then determined by the control system designed for the multivariable space of the simplified model.

During the last decade, research work has been in progress in the area of power-system-controller design, and considerable work has been done using linear dynamic system theory, the output feedback control, the multivariable root locus, and the domain separation. For large perturbations of state variables, the linear-model representation is not adequate, and there is need of nonlinear representation of synchronous machines in control system design.

Recently, some attempts have been made to design controllers for the nonlinear models of power systems. Using a dynamic programming approach, an excitation and governor controller was designed. A quasilinearization technique was used to obtain a nonlinear excitation controller. Nonlinear optimal control theory and identification methods were used to obtain a nonlinear output feedback excitation controller. Dynamic sensitivity approach was used to design a linear excitation and governor controller [4-11]

The proposed method aims at solving the difficulties and realizing the design of the nonlinear multivariable integrated excitation and governor feedback control system so that the closed-loop system is stable in a large region in state space, and asymptotically tracks the nominal terminal voltage, frequency, and tie-line power flow under load and parameter variations. The nonlinear approximate model which retains the nonlinearity of the controlled system is first developed then a nonlinear regulator is designed for the model. Then the control policy is determined which is suboptimal obtained on the basis of the quadratic index of the performance for one particular condition under s specific cost function. The developed theory is applicable to multimachine cases, especially by establishing a suitable decentralized control system theory for power systems.

PROBLEM FORMULATION

The system model used as a basis for the development of the present paper is shown in Fig. 1. It comprises a single synchronous machine feeding into an infinite bus, a prime-mover representation and an excitation system. The generator is represented by by a nonlinear third-order model based on Park's equations with , and $_f$ as the three state variables.

The synchronous machine equations are:

$$\frac{d\delta}{dt} = (\omega-1)\omega_o \quad (1)$$

$$\frac{d\omega}{dt} = \frac{1}{M}\left| k_1 h + k_2 g + k_3\omega - \frac{v_o \psi_f \sin\delta}{\tau_d x_d'} - \frac{(x_d' - x_q)}{2x_d' x_q} v_o^2 \mathrm{Sin}2 \right. \quad (2)$$

$$\frac{d\psi_f}{dt} = v_f - \frac{x_d}{\tau_d x_d'} \psi_f + \frac{(x_d - x_d')}{xd'} v_o \mathrm{Cos}\ \delta \quad (3)$$

The exciter voltage regulator and the governor system equations are:

$$\frac{dv_f}{dt} = -\frac{1}{\tau_e} v_f + \frac{\mu_o}{\tau_e}(v_o - v_s) \quad (4)$$

$$\frac{dv_s}{dt} = -\frac{v_s}{\tau_e} + \frac{\mu_s}{\tau_s} u_1 \quad (5)$$

$$\frac{dg}{dt} = -\frac{\sigma}{\tau_g} g + \frac{1}{\tau_g}\left(-\frac{\omega}{\omega_o} - g_f\right) \quad (6)$$

$$\frac{dg_f}{dt} = -\frac{1}{\tau_a} g_f + \frac{u}{\tau_a} u_2 \quad (7)$$

$$\frac{dh}{dt} = -2\frac{dg}{dt} - \frac{2}{\tau\omega} h \quad (8)$$

These equations are presented in a state variable form of

$$\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= A_1x_2 + A_2x_3\mathrm{Sin}x_1 + A_3\mathrm{Sin}2x_1 + A_4x_6 + A_5x_8 \\
\dot{x}_3 &= A_6x_3 + A_7x_4 + A_8\mathrm{Cos}x_1 \\
\dot{x}_4 &= A_9x_4 + A_{10}x_5 \\
\dot{x}_5 &= A_{11}x_5 + A_{12}u_1 \\
\dot{x}_6 &= A_{13}x_6 + A_{14}x_2 + A_{15}x_7 \\
\dot{x}_7 &= A_{16}x_7 + A_{17}u_2 \\
\dot{x}_8 &= A_{18}x_8 + A_{19}x_6 + A_{20}x_2 + A_{21}x_7
\end{aligned} \quad (9)$$

where

$x_1 = \delta$, $x_2 = \omega\ (p\delta)$, $x_3 = \psi_f$, $x_4 = v_f$,

$x_5 = v_S$, $x_6 = g$, $x_7 = g_f$, and $x_8 = h$.

The values of A_1 to A_{21} are obtained from equations (1) to (9) and the machine parameters given in the Appendix

NONLINEAR REGULATOR THEORY

The use of the nonlinear regulator theory, suggested by Wernli and Cook, is applied to the multivariable problem defined previously.

Consider the nonlinear system given in Eqn. (10)

$$\dot{Z}(t) = f(z, W, t) \quad (10)$$

For the following cost function

$$J = \frac{1}{2}\int_o^\infty \left| Z(t)^T Q Z(t) + W(t)^T R W(t) \right| dt \quad (11)$$

The suboptimal control law is given by

$$W(z,t) = -R^{-1} B^T(z,w,t) \left| \sum_{i=0}^{P} \varepsilon^i L_i(z,w,t) \right| Z \quad (12)$$

PROPOSED NONLINEAR APPROXIMATE MODEL

It is impossible to use the theory of nonlinear regulator with the existence of the Sin and Cos terms in equations (2) and (3). Therefore, it is proposed the 2nd and 3rd approximate functions of Sin and Cos, which can cover the realistic operating region. Considering the magnitude of disturbances to which the proposed control scheme is applied, the variations in the rotor angle δ (x_1) for Sin x_1, Sin $2x_1$ and Cos x_1 are thought to be within a region of $|0$ and $\Pi|$, and by using the least square method, these terms can be represented as:

$$\mathrm{Sin}\ x_1 \simeq \frac{120}{\Pi^5} x_1 (x_1 - \Pi)$$

$$\mathrm{Sin}\ 2x_1 \quad \frac{315}{4\Pi^6} 2x_1 - \Pi)(2x_1 - 2\Pi) \quad (13)$$

and $\mathrm{Cos}\ x_1 \simeq \mathrm{Sin}\ (x_1 + \frac{\Pi}{2}) \simeq \frac{315}{4\Pi^6}(x_1 + \frac{\Pi}{2})(x_1 - \frac{3\Pi}{2})$

Substituting these terms in the state equations, the $\dot{x}_2$ and $\dot{x}_3$ equations are given as:

$$\dot{x}_2 = A_1x_2 + A_2x_3\left|\frac{120}{\Pi^5} x_1(x_1 - \Pi)\right| + A_3 \frac{315}{4\Pi^6} 2x_1(2x_1 - \Pi)\cdot (2x_1 - 2\Pi) + A_4x_6 + A_5x_8 \quad (14)$$

$$\dot{x}_3 = A_6x_3 + A_7x_4 + A_8\left|\frac{315}{4\Pi^6}(x_1 + \frac{\Pi}{2})(x_1 - \frac{3\Pi}{2})\right| \quad (15)$$

Taking the Taylors Series expansion of Eqn. (9) around the arbitrary operating points x_i^o and u_i^o , it follows:

$$\Delta\dot{x} = \left| A_o + \Delta A_1(\Delta x_1) + \Delta A_3(\Delta x_3) + \Delta A_{11}(\Delta x_1^2) \right| \Delta x + B_o \Delta u \quad (16)$$

where A_o is constant part given by Eqn. (17), ΔA_1 (Δx_1) is the first term of the variable part and a function of Δx_1, given by Eqn. (18), $\Delta A_3(\Delta x_3)$ is the second term and is a function of Δx_3, given by Eqn. (19) and $A_{11}(\Delta x_1^2)$ is the third term, is a function of x_1^2 , given by Eqn. (20). B_o is given by Eqn. (21).

$$A_0 = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ (\frac{\partial f_2}{\partial x_1})^0 & A_1 & (\frac{\partial f_2}{\partial x_3})^0 & 0 & 0 & A_4 & 0 & A_5 \\ (\frac{\partial f_3}{\partial x_1})^0 & 0 & A_6 & A_7 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & A_9 & A_{10} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & A_{11} & 0 & 0 & 0 \\ 0 & A_{14} & 0 & 0 & 0 & A_{13} & A_{15} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & A_{16} & 0 \\ 0 & A_{20} & 0 & 0 & 0 & A_{19} & 0 & A_{18} \end{bmatrix} \quad (17),$$

$$\Delta A_1(\Delta x_1) = \Delta x_1 \cdot \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{2}(\frac{\partial^2 f_2}{\partial x_1^2}) & 0 & (\frac{\partial^2 f_2}{\partial x_1 \partial x_3})^0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{2}(\frac{\partial^2 f_3}{\partial x_1^2}) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (18),$$

$$\Delta A_3(\Delta x_3) = \Delta x_3 \cdot 0 \quad (19),$$

$$\Delta A_{11}(\Delta x_1^2) = \Delta x_1^2 \cdot \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{3!}(\frac{\partial^3 f_2}{\partial x_1^3})^0 & 0 & \frac{1}{2}(\frac{\partial^3 f_2}{\partial x_1^3 \partial x_3})^0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{3!}(\frac{\partial^3 f_3}{\partial x_1^3})^0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (20),$$

and

$$B_o^T = \begin{bmatrix} 0 & 0 & 0 & 0 & A_{12} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & A_{17} & 0 \end{bmatrix} \quad (21)$$

For comparison, the linearized model is given below:

$$\Delta\dot{x} = A\ \Delta x + B\ \Delta u \quad (22)$$

where

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ A_2 \mathrm{Cos} X_1^0 . x_3^0 + 2A_3 \mathrm{Cos} 2x_1^0 & A_1 & A_2 \mathrm{Sin} x_1^0 & 0 & 0 & A_4 & 0 & A_5 \\ -A_8 \mathrm{Sin} x_1^0 & 0 & A_6 & A_7 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & A_9 & A_{10} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & A_{11} & 0 & 0 & 0 \\ 0 & A_{14} & 0 & 0 & 0 & A_{13} & A_{15} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & A_{16} & 0 \\ 0 & A_{20} & 0 & 0 & 0 & A_{19} & A_{21} & A_{18} \end{bmatrix} \quad (23)$$

and $B = B_0$ (24)

Here, three models have been exercised namely, Non-Linear Model, presented by Eqns. (19), Nonlinear Approximate Model, presented by Eqns. (9), (14), (15), (17-21), and the Linearized Model expressed by Eqns. (22-24).

Figure 2 shows the angular velocity courses of the autonomous system for a specific initial condition value

$$x(0) = \text{col.}\ [0 \quad 1.0 \quad 10.5 \quad 1.05 \quad 0 \quad 0 \quad 0 \quad 0]$$

at the following operating conditions:

$X_1^0 = 1.0$, $x_2^0 = 1.0$, $x_3^0 = 10.5$, $x_4^0 = 1.05$, $x_5^0 = 0$, $x_6^0 = 0$,

$x_7^0 = 0$ and $x_8^0 = 0$.

Comparing the results of the 3 models, we can observe that the nonlinear approximate model retains the dynamics of the nonlinear model better than the linearized model on the whole. The difference is particularly clear from the magnitude of the oscillations.

DESIGN OF SUBOPTIMAL NONLINEAR REGULATOR

To design a suboptimal nonlinear regulator for the nonlinear approximate model derived previously, it is required to determine the suboptimal control law which minimizes the following cost functional.

$$J = \frac{1}{2} \int_0^{\infty} \left[\Delta x(t)^T Q \Delta x(t) + \Delta u(t)^T R \Delta u(t)\right] dt \quad (25)$$

where the assumed weighting matrices Q and R are as follows:

$Q = I_8$ (Unit matrix of 8 x 8)

and $R = I_2$ (Unit matrix of 2 x 2) .

Rewriting Eqn. (16) as follows:

$$\Delta x = [A_o + \Delta A(\Delta x)]\, \Delta x + B_o\, \Delta u \quad (26)$$

Taking up to the second term of Eqn. (12) for convenience the desired control law v is determined as follows:

$$\Delta u = -R^{-1} B_o^T [L_0 + L_1(\Delta x)]\, \Delta x \quad (27)$$

where L_0 and $L_1(\Delta x)$ are given as:

$$L_0 = \begin{bmatrix} -0.215 & 0.041 & -0.121 & 0.101 & 0.252 & -0.014 & 0.086 & 0.115 \\ 0.042 & -0.007 & 0.106 & -0.046 & -0.112 & 0.099 & -0.023 & 0.061 \end{bmatrix}$$

$$L_1(\Delta x) = \Delta x_1 \begin{bmatrix} 0.006 & -0.001 & -0.035 & -0.001 & -0.008 & -0.003 & 0.062 & 0.009 \\ 0.018 & -0.000 & 0.028 & -0.003 & -0.014 & +0.003 & 0.045 & 0.009 \end{bmatrix}$$

$$+\Delta x_1^2 \cdot \begin{bmatrix} 0.065 & 0.012 & 0.010 & 0.008 & 0.062 & 0.001 & 0.003 & 0.006 \\ -0.061 & -0.006 & -0.030 & -0.002 & -0.001 & -0.003 & 0.005 & 0.002 \end{bmatrix}$$

ADAPTABILITY TO LARGE DISTURBANCES AND CHANGES OF OPERATING POINTS

For large disturbances, the nonlinear regulator has given much better results than the linear one. For the changes of operating points, the first point which is the initial is used to construct the nonlinear approximate model and the nonlinear regulator is designed as the first state, and applied is the second state. The values of these two states are given below.

First state $X^{0(1)} = \text{col.}[0.98 \;\; 1.0 \;\; 9.5 \;\; 1.02 \;\; 0 \;\; -0.01 \;\; 0 \;\; 0]$

Second state $X^{o(2)} = \text{col.}[0.945 \;\; 1.0 \;\; 8.2 \;\; 1.05 \;\; -0.01 \;\; -0.02 \;\; 0 \;\; -0.03]$

The response curves of the rotor angle for a specific initial value $x(0) = \text{col.}|1.0 \;\; 1.0 \;\; 10.5 \;\; 1.05 \;\; 0 \;\; 0 \;\; 0 \;\; 0|$. It is clearly shown that the proposed regulator is superior than the linear one.

Figure 4 shows the controls u_1 and u_2 for the three designs. Figure 5 shows the states obtained when these three controls are applied to the system. From Figs. 4 and 5, it is clear that the nonlinear regulator gave the solution very close to the nonlinear approximate model while the linear solution is quite away from the nonlinear one.

CONCLUSIONS

A linear control strategy does not guarantee desirable performance unless the system with the proposed strategy is analyzed for its stability. The primary purpose of this work was to construct and design a multivariable control system consisting of governor and exciter control systems which is adaptable to large disturbances and changes of operating points, to obtain a better dynamic response and to increase the damping torques. As seen from the results, the feedback gain of the nonlinear regulator is a kind of dynamic gains, and from that sense the proposed system is said to be a more advanced regulator than the conventional linear ones.

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APPENDIX

The following numerical values are used for the system variables:

$x_d = 1.0$ $x_d = 0.5$ $x_q = 0.6$ $\tau_o = 10.0$ $\tau_s = 0.20$
$M = 5.0$ $\omega_o = 1.0$ $\mu_e = 2.5$ $\tau_e = 0.25$ $\mu_s = 2.0$
$\sigma = 0.45$ $\tau_g = 0.10$ $u_a = 1.0$ $\tau_a = 1.0$ $\tau_\omega = 0.5$
$k_1 = 1.67$ $k_2 = -1.52$ $k_3 = 0.217$ and $v_o = 1.05$

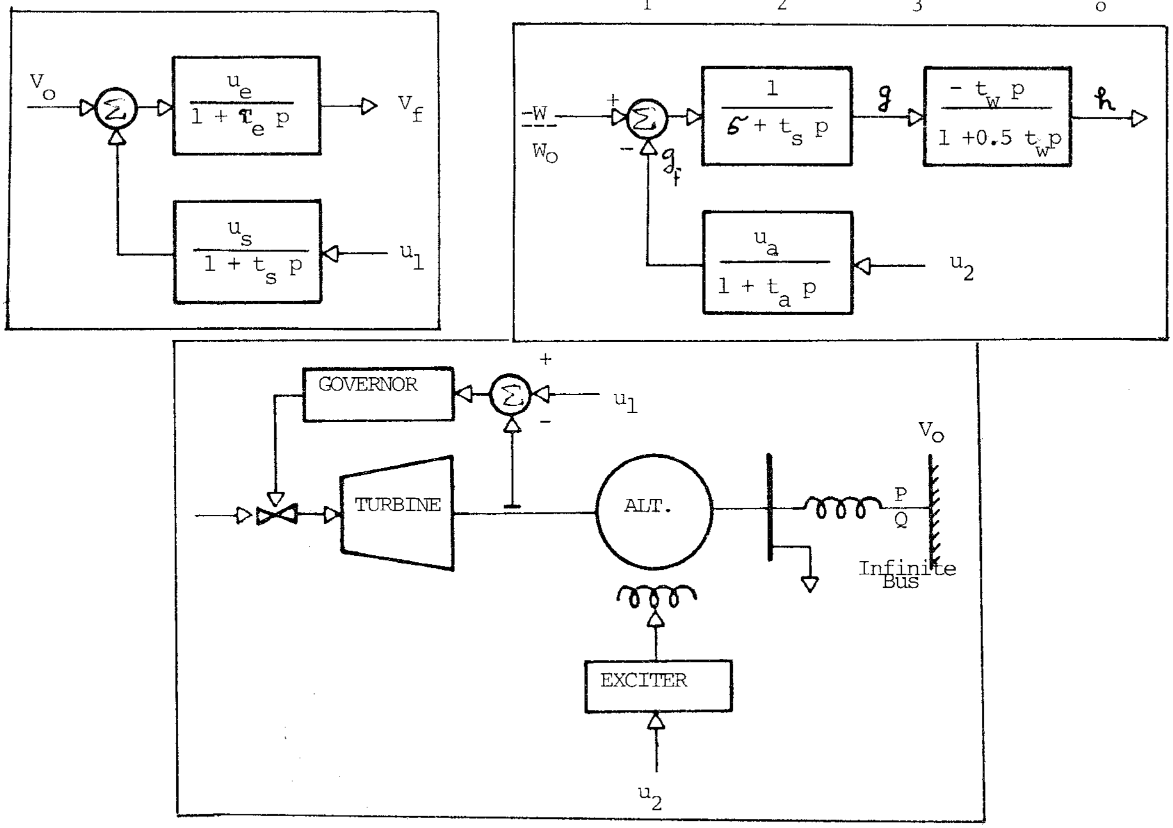

Figure 1. Block diagram of model System.

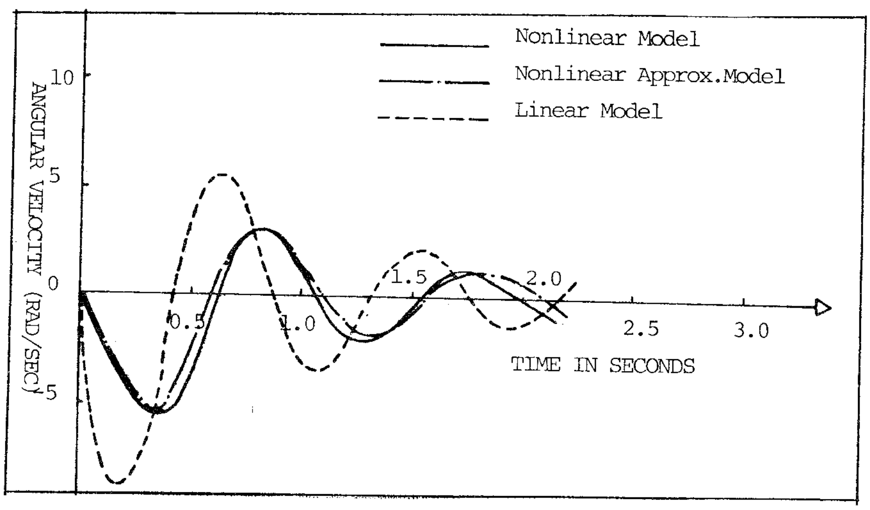

Figure 2. Effect of nonlinear approximate model.

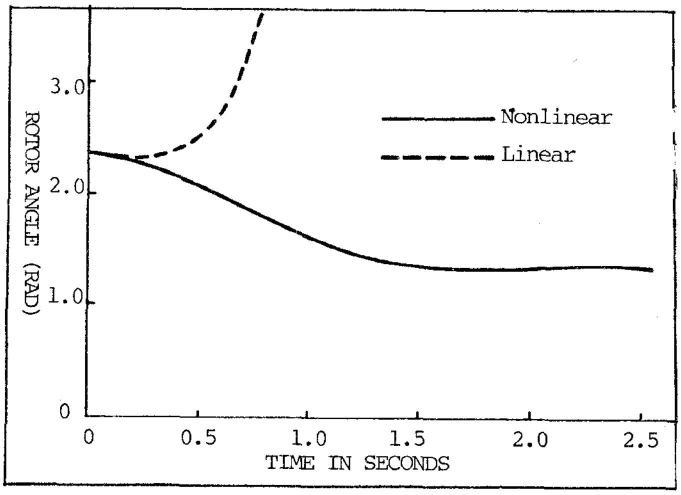

Figure 3. Suboptimal Control at different operating points.

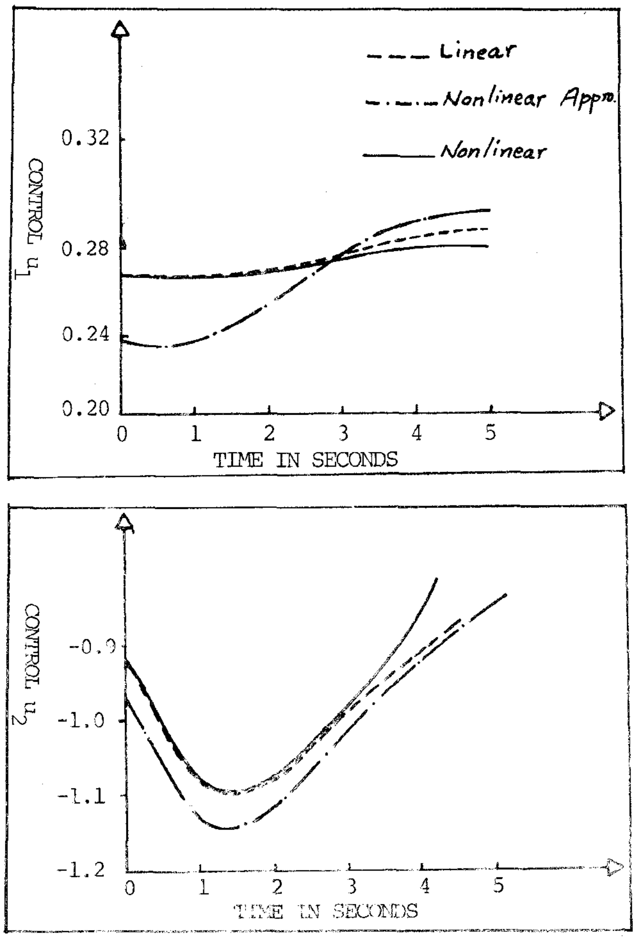

Figure 4. Different exciter and Governor Controls.

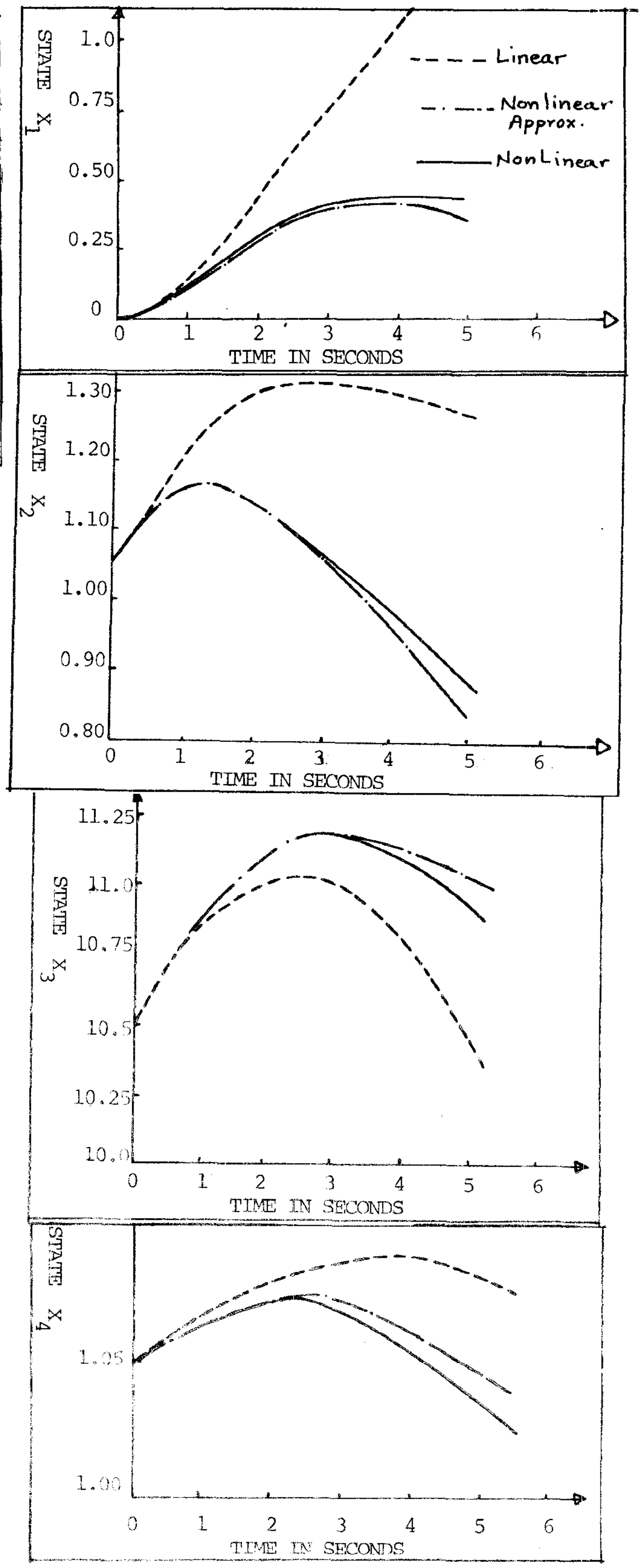

Figure 5. Behavior of state variables for various controls.