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OPTIMIZATION OF GOVERNOR PERFORMANCE USING FEEDFORWARD CONTROL PHILOSOPHY

BY

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ABSTRACT:

In this paper a technique for parameter adjustment of feedforward path controller is introduced. The adjustment procedure uses information contained in the sensitivity of the system outputs. Adjustable parameters of major concern are those which will force the system responses towards their steady state values. The method offers the possibility of site adjustment on real plant without prior system identification. Adjusting the parameters of a simplified model power system has been investigated.

1. INTRODUCTION:

Optimal and suboptimal control proved to be powerful and elegant in dealing with problems of linear control theory specially for multi-variable systems (1,2). However, the application of techniques used in such control systems to "actual" systems requires adequate identification of the system to be controlled, so that the design and settings for a mathematical model of the system will be applicable to the real system itself. Such identification, however, is generally a formidable task specially for practical system.

An alternative strategy has been suggested by Ibrahim (3). Improved Sensitivity method, for the optimisation of synchronous generator excitation system through the adjustment of the variable parameters within the controller is achieved.

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The method has been presented with a controller in the feedback path. It has been shown[4] that the method is capable of producing settings for the feedback parameters in similar fashion to that of the conventional optimal and suboptimal techniques. In addition the method offers these advantages:

i) explicit plant identification is not necessary;

ii) in general the technique is similar to that used by plant comissioning engineers involving a series of tests and parameter adjustment steps;

iii) information can be provided on the effects on time responses of proposed parameter changes;

iv) undesirable oscillatory modes can be suppressed as the adjustment process proceeds by adjusting the relative importance of the output variables (cf. weighting matrix of optimal control) giving a time domain equivalent of dominant eigenvalue shifting in some optimal control schemes[5].

An alternative or in addition to the feedback controller, it is possible to introduce phase compensation networks into the feedforward paths of the controllers, to introduce the required amount of phase shift. This phase shift will most effectively damp any oscillations. Feedforward controller can be effectively used in the governer loop to increase the damping of the turbo-alternator, and thus increase its steady state operating range. Adjustment of the parameters of this feedforward controller is often needed, so that it must be capable of supplying sufficient damping, to ensure dynamic stability. At the same time this control also affects the transient performance, This adjustment can be done by the use of frequency response tests, carried out on simulations of the system, as guidelines, and then "tune" the controller on-site to obtain the final settings.

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There is no guarantee with this approach, that the hopefully improved response is necessarily the best possible response of the system. The main goal of the present work is the introduction of a sensitivity technique suitable for adjusting the parameters of the feedforward controller in an optimum fashion. A practical system is used for illustration.

2. IMPROVED SENSITIVITY METHOD:

The improved sensitivity method[4] requires only information about the output of the system. Perturbed output are obtained using a step signal at the controller reference input. Sensitivity functions are then expressed in terms of these perturbed outputs. These functions are used in predicting optimal settings for controller parameters. The equations which describe the model system with a controller in the feedback path, are:

$$y_i(s) = W_i(s) \cdot v(s) \text{ for } 1 \leqslant i \leqslant n \qquad \text{.....(1)}$$

$$v(s) = K_r/s - \sum_{j=1}^{n} K_j \cdot y_j(s) \qquad \text{.....(2)}$$

where y_i is the ith state variable,

W_i is the ith transfer function relation $y_i(s)$ to $v(s)$

v is the single input control,

K_r/s is the step disturbance of magnitude K_r,

K_j is the jth feedback parameter, and

s is the laplace operator.

A quadratic system performance index is defined as:

$$J = \tfrac{1}{2} \int_0^{\infty} \left[\sum_{i=1}^{n} (y_{fi} - y_i)\, Q_i (y_{fi} - y_i) + (v_f - v)\, r (v_f - v) \right] dt \qquad \text{.....(3)}$$

where y_f and v_f are final values of the system output and input, and Q_i and r are weighting factors. The sensitivity method computes the feedback parameters $\underline{K}$ so as to minimise the performance index J when the system is started from zero initial conditions (y_o=0) and permitted to settle to steady state conditions at which y is y_f.

Substitution of equation (2) into equation (1) gives:

$$y_i(s) = \frac{w_i(s)\ K_r/s}{1 + \sum_{j=1}^{n} K_j\ W_j(s)} \qquad .....(4)$$

From our previous experience in designing feedback controller[4] the step size K_r would be defined as an appropriate function of the feedback parameters. It takes the following form:

$$K_r = 1 + \sum_{j=1}^{n} K_j\ Y_{f_j} \qquad .....(5)$$

This particular choice will make the feedback law equivalent to the one calculated using classical optimal control method, however with the advantage of on-site adjustment. The sensitivity of variable y_i with respect to parameter K_j is then expressed as follow:

$$S_{k_j}^{y_i} = \frac{\partial y_i}{\partial K_j} = \frac{\partial}{\partial K_j}\left(\frac{W_i(s)}{1 + \sum_{j=1}^{n} K_j W_j(s)}\right).\ K_r/s\ +$$

$$\frac{1/s\ .\ W_i(s)}{1 + \sum_{j=1}^{n} K_j W_i(s)}\ .\ \frac{\partial K_r}{\partial K_j} \qquad .....(6)$$

For computational purposes this equation is reformulated in sampled data form as:

$$S_{k_j}^{y_i}(\gamma \cdot \Delta t) = \frac{1}{K_r}\left[\sum_{\beta=1}^{\gamma} - \frac{y_i(\beta \cdot \Delta t) - y_i(\beta - 1) \cdot \Delta t)}{t} \cdot y_j(\gamma, \Delta t - \beta \cdot \Delta t)\right] + \frac{1}{K_r} \cdot y_{f_j} \cdot y_i(\gamma \cdot \Delta t) \quad \ldots\ldots(7)$$

Where:

γ = number of samples

Δt= sampling interval

$y_i(o) = 0$ for $1 \leqslant i \leqslant n$.

It should be noted that the accuracy of the sensitivity function, equation (7), depends upon the value taken for the time interval Δt. The samller this value, the higher is the accuracy. On the other hand, the choice of a very small time interval makes the use of this algorithm costly in computer time. A value of 0.02 second for Δt is found suitable.

Hjk it has been shown[4] that the sensitivity functions, given by equation (7), can be used to calculate the feedback parameters K_j for all j.

3. SENSITIVITY FUNCTION FOR FEEDFORWARD-PATH CONTROLLER:

The model system with a controller in the forward path is shown in Fig.(1). However, this schematic diagram differs from the conventional feedforward controller in that, its parameters is adjusted on-site based on sensitivity measure equation (7). Moreover the design procedure does not require prior knowledge of the parametric structure of the controlled system. This point offers great advantages when we are dealing with a large scale system like a power plant.

Element of Fig.(1) are:

$C(s, \alpha_j)$ $j = 1, m$ is a controller with m adjustable parameters.

$W(s)$ is unidentified system which is being controlled.

$y_i(s)$ $i = 1, n$ is the resultant change in the ith output.

$G_i(s)$ is the transfer function relation $T(s)$ to $y_i(s)$.

$V_r(s)$ is a step disturbance to the controller reference.

K_r is a scaling factor.

The following relations can be easily obtained from Figure (1);

$$E(s) = V_r(s) - y_i(s) \qquad \text{......(8)}$$

$$y_i(s) = E(s)\, C(s, \alpha_j)\, W(s)\, G_i(s) \qquad \text{......(9)}$$

$$V_r(s) = K_r/s \qquad \text{......(10)}$$

Using equations (8, 9) and (10) we obtain;

$$y_i(s) = \frac{W(s)\, C(s, \alpha_j)\, G_i(s)}{1 + C(s, \alpha_j) W(s) G_i(s)}\, K_r/s \qquad \text{......(11)}$$

The sensitivity function of the state variable y_i with respect to the adjustable parameter α_j is defined as[4]

$$S_j^{y_i} = K_r/s \frac{\partial}{\partial \alpha_j} \left(\frac{W(s)\, C(s, \alpha_j)\, G_i(s)}{1 + C(s, \alpha_j)\, W(s)\, G_i(s)} \right) +$$

$$\frac{W(s)\, C(s, \alpha_j)\, G_i(s)}{1 + C(s, \alpha_j)\, W(s)\, G_i(s)} \; \frac{\partial K_r}{\partial \alpha_j} \qquad \text{......(12)}$$

Since the controller function is to improve the dynamic response of the system due to unpredicatable changing conditions a propper form would be:

$$C(s, \alpha_j) = \frac{1 + s\,\alpha_1}{1 + s\,\alpha_2}$$

Using this form of controller the final values of the system responses are fixed for all values of the adjustable parameters α_1 and α_2 therefore the scale factor K_r is constant rather than a function of the system's final values. Then the second term from equation (12) is vanished and the sensitivity function becomes;

$$S^{y_i}_{\alpha_j} = K_r/s \; \frac{\partial}{\partial \alpha_j} \left(\frac{W(s)\, C(s,\alpha_j)\, G_i(s)}{1 + C(s,\alpha_j)\, W(s)\, G_i(s)} \right) \quad \ldots\ldots(13)$$

$$= K_r/s \; \frac{1 + C(s,\alpha_j) W(s)\, G_i(s)\; W(s)\, G_i(s)}{\left[1 + C(s,\alpha_j)\, W_i(s)\, G_i(s)\right]^2} \cdot \frac{\partial C(s,\alpha_j)}{\partial\, \alpha_j} -$$

$$\frac{W(s)\, C(s,\alpha_j)\, G_i^2(s)\, W(s)}{\left[1 + C(s,\alpha_j)\, G_i(s)\, W_i(s)\right]^2} \cdot \frac{\partial C(s,\alpha_j)}{\partial \alpha_j}$$

$$= \frac{K_r}{s} \; \frac{W(s)\, G_i(s)}{\left[1 + W(s)\, C(s,\alpha_j) G_i(s)\right]^2} \cdot \frac{\partial C(s,\alpha_j)}{\partial \alpha_j} \quad \ldots(14)$$

Equation (14) can be rewritten as a function of the system output as;

$$S^{y_i}_{\alpha_j} = \frac{y_{i(s)}}{1 + W(s)\, C(s,\alpha_j) G_i(s)} \; \frac{1}{C(s,\; \alpha_j)} \; \frac{\partial}{\partial \alpha_j} C(s,\; \alpha_j). (15)$$

. Moreover, from Figure (1), the error signal

$$E(s) = \frac{K_r}{s} \; \frac{1}{1 + W(s)\, C(s,\; \alpha_j)\; G_i(s)} \quad \ldots\ldots(16)$$

Substitution of the error equation (16) into the sensitivity equation (15) gives;

$$S_{\alpha_j}^{y_i} = \frac{1}{k_r} \; s \, y_i(s) \frac{E(s)}{C(s, \alpha_j)} \frac{\partial}{\partial \alpha_j} C(s, \alpha_j)$$

Where, j = 1, 2

If we define a new function $F_j(s)$ as

$$F_j(s) = \frac{1}{C(s, \alpha_j)} \frac{\partial C(s, \alpha_j)}{\partial \alpha_j} \quad ......(17)$$

We can call the sensitivity signal for parameter α_j as,

$$Z\,\alpha_j = E(s)\, F_j(s) \quad ......(18)$$

Therefore the sensitivity function to parameter α_j is given by:

$$S_{\alpha_j}^{y_i}(s) = \frac{1}{k_r}\, s \,.\, y_i(s)\, Z\,\alpha_j\,(s) \quad ......(19)$$

The inverse transform of equation (19) is given by:

$$S_{\alpha_j}^{y_i}(t) = \frac{1}{k_r} \int_0^t \frac{d}{d\tau}\, y_i(\tau)\, Z_{\alpha_j}(t - \tau)\, d\tau \quad .....(20)$$

Which, in sample data form, becomes

$$S_{\alpha_j}^{y_i}(\gamma . \Delta t) = (1/k_r) \sum_{B=1}^{\gamma} y_i(\beta . \Delta t) . Z_{\alpha_j}(\gamma . \Delta t - \beta . \Delta t) . \Delta t \quad ......(21)$$

Where $y_i(\beta . \Delta t) = \dfrac{y_i(\beta . \Delta t) - y_i((\beta - 1) . \Delta t)}{\Delta t}$

4. <u>Problem Solution Technique:</u>

The output response $y_i(t, \alpha + \Delta\alpha)$ due to change $\Delta \underline{\alpha}$ in the parameters $\underline{\alpha}$ is related to the original response before the changes occur, $y_i(t, \alpha)$ by the equation:

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$$y_i(t, \alpha_j + \Delta\alpha_j) \simeq y_i(t, \alpha) + \sum_{j=1}^{n} \frac{\partial y_i(t, \alpha_j)}{\partial \alpha_j} . \Delta\alpha_j \quad \ldots(22)$$

Substituting the definition of sensitivity used in equation (6) yields;

$$y_i(t, \alpha_j + \Delta\alpha_j) = y_i(t, \alpha_j) + \sum_{j=1}^{n} \Delta\alpha_j . S_{\alpha_j}^{y_i}(t) + Ry_i \quad \ldots..(23)$$

Where, Ry_i is the residual corresponding to higher order terms.

Given that the sensitivity functions are known, the approximate changes in the state variable response due to change in one or' more of the parameters can be predicted. These functions will be used here, however, to permit the estimation of the parameter changes which are necessary to alter the response from its present form towards its final form "y_f". Ideally the i-th final value yf_i is accomplished by making the parameter changes $\Delta\alpha_j$ for all j giving

$$y_i(t, \alpha_j + \Delta\alpha_j) = y_{f_i}$$

$$\text{i.e. } y_{f_i} = y_i(t, \alpha_j) + \sum_{j=1}^{n} \Delta\alpha_j S_{\alpha_j}^{y_i} + Ry_i(t) \quad \ldots..(24)$$

It is then possible to choose all $\Delta\alpha_j$ so as to minimize $Ry_i(t)$. Minimisation of $Ry_i(t)$ is possible in the integral least squared error form given by equation (3). The minimisation index can therefore expressed as:

$$J = \tfrac{1}{2} \int_0^T \sum_{i=1}^{n} Q_i \left[Ry_i(t) \right]^2 dt$$

$$\text{i.e. } J = \tfrac{1}{2} \int_0^T \sum_{i=1}^{n} Q_i \left[(y_{f_i} - y_i(t, \quad _j)) - \sum_{j=1}^{n} S_{\alpha_j}^{y_i} \right]^2 dt \quad ..(25)$$

or alternatively in the discrete form as:

$$J = \frac{1}{2} \sum_{\beta=1}^{\gamma} \sum_{i=1}^{n} Q_i \left[(y_{f_i} - y_i(\beta.\, \Delta t)) - \sum_{j=1}^{n} S_j^{y_i} (\beta.\, \Delta t) \right]^2 .\Delta t \qquad \text{......(26)}$$

It is then possible to minimize the performance index J with respect to the parameter changes $_j$ by differentiating J with respect to each of the parameter changes in turn and equating the derivatives to zero, i.e.

$$\partial J / \partial \alpha_j = 0 \text{ for } 1 \leqslant j \leqslant n \qquad \text{.....(27)}$$

This constitutes a set of simultaneous equations. Solution of this set renders the necessary changes in the controller parameters. Implementation of these changes on the system improves the system characteristics. The process is iterated until equation (27) is satisfied.

5. IMPLEMENTATION OF SENSITIVITY TECHNIQUE:

For the purpose of this study a nonlinear model of a synchronous machine supplying an infinite bus with voltage V_∞ through an external reactance X_e is used[6]. The field voltage of the machine is modified by an automatic voltage regulator and exciter. The model is described, along with the appropriate parameters in Appendix I. The steam valve and governer model fitted to the test set is typical of a modern electro-hydraulic governer. The system also, includes a cascade compensator. However, the performance of the complete set is unsatisfactory. Therefore the proposed technique as explained in the previous section is used to obtain the optimal setting of the cascade compensator parameter in order to improve the dynamic stability of the system. A block diagram of the over-all system under study is shown in Fig.(2).

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A step size of one per cent is chosen as a disturbance. With this step size a non-linear model is used. The performance index J, equation (26), is formed using three key variables in the system. The three state variables are rotor slip, rotor angle, and turbine mechanical torque. The weightings for these variables in the performance index are 1.0, 1.0, and 100.0 respectively based on physical reasoning. The initial operating conditions are taken as:

$$P_o = 0.8 \qquad Q_o = 0.0 \qquad V_{t_o} = 1.0$$

The system is simulated and the state variable responses resulted from the step disturbance are stored at 0.02 s intervals for 5s. The sensitivity calculations are based on equations (18) and (19), where in this case

$$F_j(s) = \frac{1}{C(s, \alpha_j)} \frac{\partial C(s, \alpha_j)}{\partial \alpha_j}$$

thus $F\alpha_1(s) = \dfrac{s}{1 + s\alpha_1}$ and $F\,\alpha_2(s) = \dfrac{-s}{1 + s\alpha_2}$

The sensitivity signals are then given in terms of the error E(s), which is computed from the stored variables, such that

$$Z\,\alpha_1(s) = \frac{s}{1 + s\,\alpha_1}\,E(s)$$

$$Z\,\alpha_2(s) = \frac{-s}{1 + s\,\alpha_2}\,E(s)$$

The digitized equivalence of these relationships are

$$Z\,\alpha_1(\gamma\,.\,\Delta t) = \Big[\,2\,\alpha_1(E\,(\gamma\,-1)\,\Delta t - E(\gamma\,.\,\Delta t)) - (\Delta t - 2\,\alpha_1).$$

$$Z\alpha_1(\gamma\,-1)\,\Delta t\,\Big]/(\,\Delta t + 2\,\alpha_1)$$

$$Z\alpha_2(\gamma.\Delta t) = -\left[2\ \alpha_2(E\ ((\gamma-1)\ \Delta t - E\ (\gamma\ .\ \Delta t)) - (\Delta t - 2\alpha_2).\ Z\ \alpha_2(\gamma - 1)\ \Delta t\right] / (\Delta t + 2\alpha_2)$$

Having calculated the sensitivity singal Z_j, the sensitivity functions are then computed. These sensitivity functions are then used in the set of equations (25) from which the parameter changes $\Delta\alpha_j$ for all j are computed.

The study performed on the model system started with values $\alpha_1 = 0.1$, and $\alpha_2 = 0.0025$ for the compensated network, and a performance index of 0.325×10^{-2}. From Fig.(3) the system is shown to be slightly damped. After four iterations of the process, the index is reduced to 0.271×10^{-2} with $\alpha_1 = 0.31$ and $\alpha_2 = 0.0012$.
The system responses after four iterations of the process are also shown in Fig.(3). It can be seen that adjustment of the controller's parameters considerably improves the system responses.

6. CONCLUSION:

A technique based on parameter sensitivity functions to adjust the compensator parameters has been presented. The method obviates the necessity of linearising the system equations. Therefore a mathematical model is not needed for on-site purpose. Instead the method can be implemented directlly on existing plants. Actually what is needed is the output of structurally unknown system.

Simulation study shows that the optimum controller settings, obtained by the proposed technique, results in a considerably improved system response.

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APPENDIX I

The equations describing the model system used in this study are -

$$s^2\delta = T_m - T_{el} - D.s\,\delta \quad /M$$

$$T_{el} = V_d\, I_d + V_q\, I_q$$

$$I_q = V_\infty \sin\delta \;/(X_e + X_q)$$

$$I_d = (V_q - V_\infty \cos\delta\,)/(X_e + X'_d)$$

$$V_d = V'_q - X'_d\, I_d$$

$$V_q = X_q\, I_q$$

$$s.V'_q = \frac{1}{T'_{do}} \quad V_f - (X_d - X'_d)\, I_d - V'_q$$

$$V_t = (V_d^2 + V_q^2)^{1/2}$$

V_f is modified by the A.V.R. and the exciter as follows:

$$V_f = \frac{G_1(1 + sT_1)(1 + sT_3)}{(1 + sT_2)(1 + sT_4)} \quad \frac{G_2}{(1 + sT_e)}\,(V_R - V_t)$$

Where;

T_e is the exciter time constant $T_1 - T_4$ are phase compensation parameters G_1, G_2 are fixed gains.

The following are values of the fixed parameters used in this study.

$D = 0.01$	$M = 0.0228$
$X_e = 0.5$ p.u.	$X_d = 1.957$ p.u.
$X_q = 1.927$ p.u.	$X'_d = 0.25$ p.u.
$T'_{do} = 5.3$ S	$G_1 = 13.4$
$G_2 = 15.0$	$T_e = 1.8$ S.
$T_1 = 0.065$ S	$T_2 = 0.047$ S.
$T_3 = 3.0$ S	$T_4 = 3.51$ S.

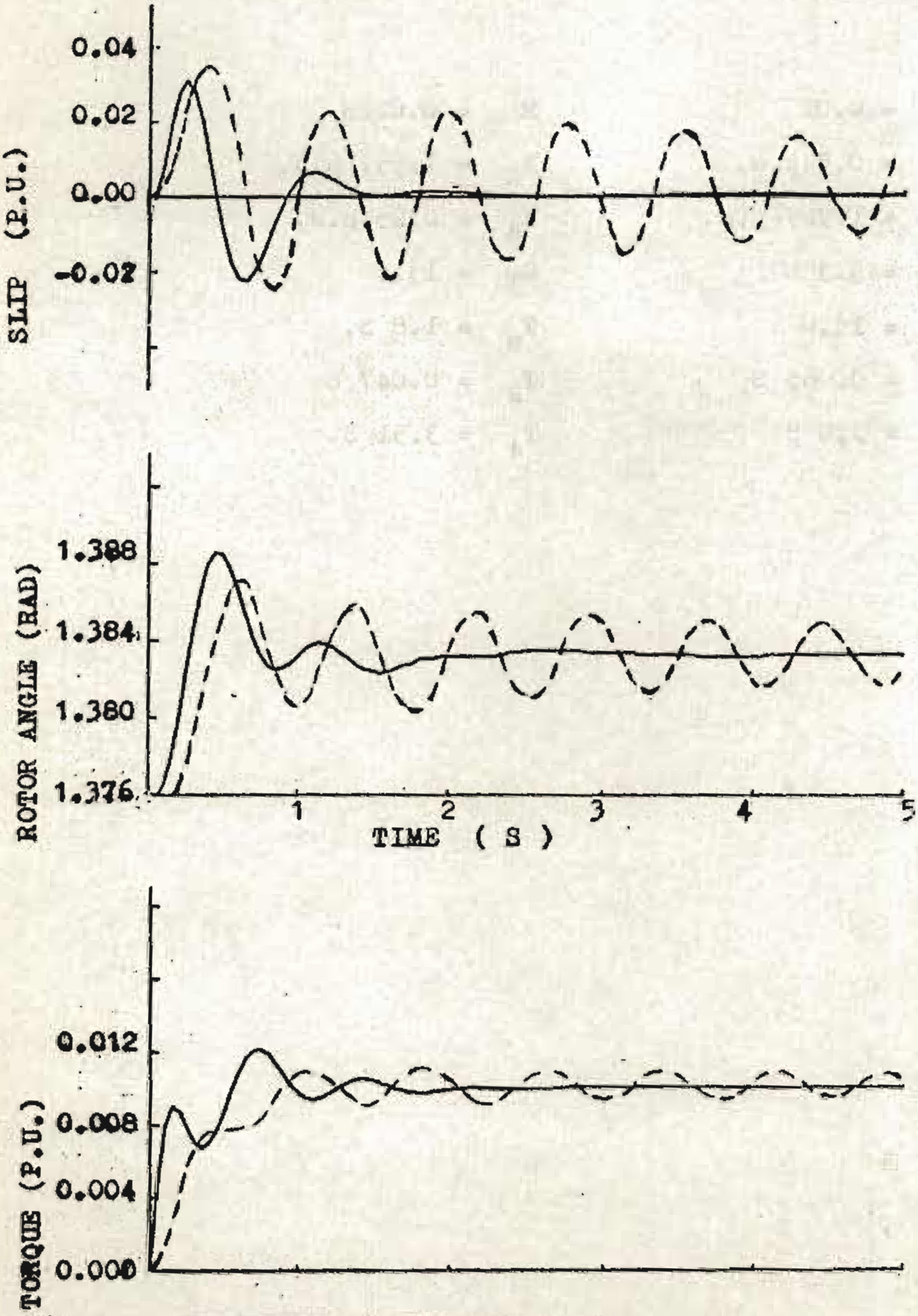

Figure 3 RESPONSES OF THE MODEL POWER SYSTEM

- - - - - Before adjustment

——— After adjustment

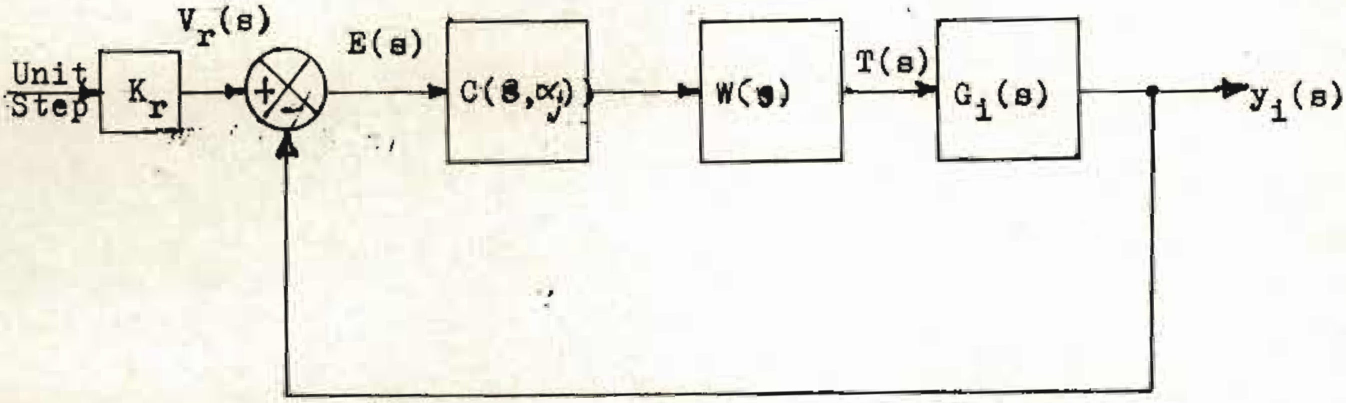

Figure 1 MODEL SYSTEM FOR THE IMPROVED SENSITIVITY METHOD

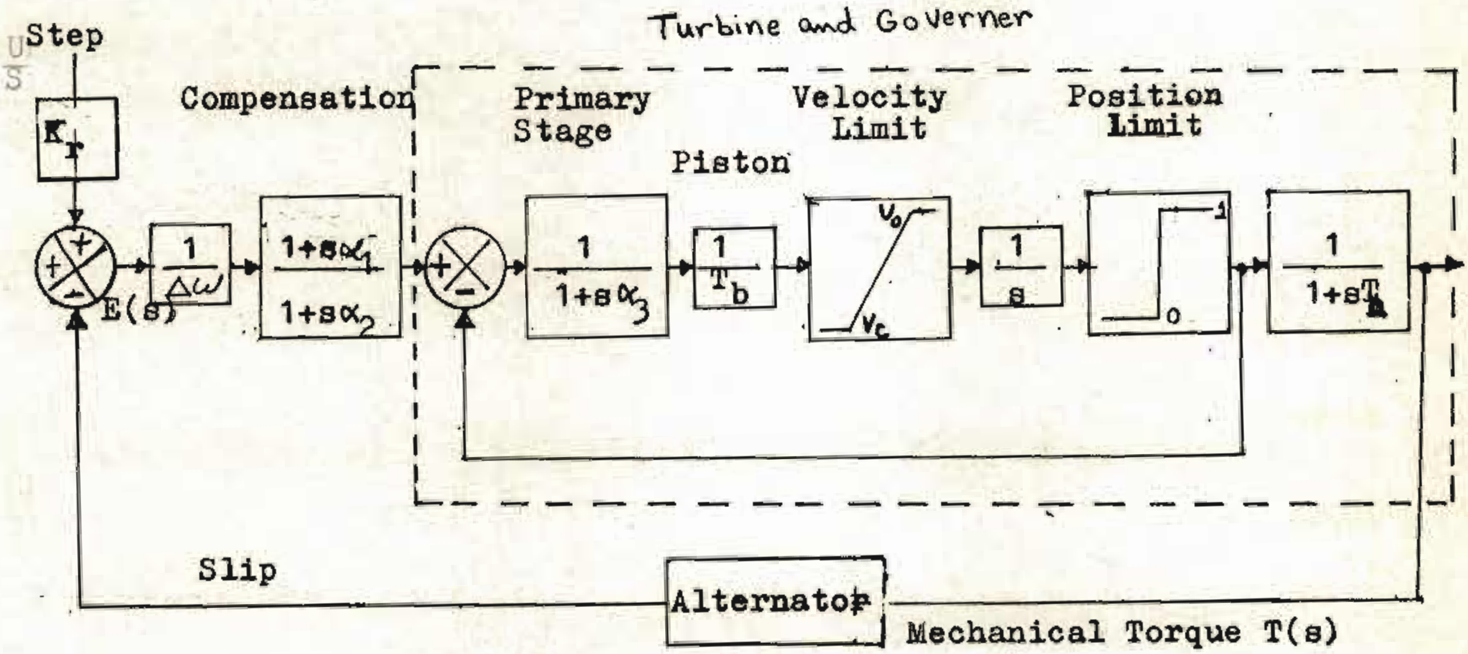

Figure 2 MODEL SYSTEM REPRESENTATION

$\Delta\omega = 0.04$ $V_o = 4.0$ pu/s $V_c = 6.6$ pu/s $T_h = 0.2$ s $T_b = 0.1$ s

$\alpha_3 = 0.01$