# MODELLING THE NIGERIAN POWER SYSTEM FOR AUTOMATIC GENERATION CONTROL
# PART II: SIMULATION STUDIES OF THE POWER PLANT RESPONSE

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**ABSTRACT**

In this second part of the two part serial, experimentation on the derived models with standard test signals is carried out. The aim is to compare the plant response under different operating conditions. The effects of the non-linearities mentioned in part one on the plant response are exposed. Finally integral control action is imposed on the model and several operating conditions simulated to show the inadequacy of the integral controller especially under wide variations of frequency.

## INTRODUCTION

The process of analytically modelling a non – linear plant like a typical power system, definitely involves some degree of imprecision which accounts for the difference between the response of the model and that of the plant to the same input signal. Under real life conditions, the response requirements of a power system are determined by the characteristics of the connected load. The objective of simulation studies of Automatic Generation Control (AGC) therefore is to synthesize the various possible load characteristics and impose them on power system models so as to investigate the efficacy of proposed operation strategies or controls.

Several techniques have been reported in the technical literature for modelling a power system for AGC studies [ 1 – 4 ]. One basic problem that arises is how to co-ordinate hydro – governing systems with their steam counterparts [5]. It is therefore standard practice in power system modelling for AGC studies to assume that a given control area (like Nigeria for instance) consists of either predominantly hydro or steam /gas generating plants. Based on this assumption, three AGC models are proposed for the Nigerian power system representing three possible operating strategies – viz.

(i) A single control area consisting of predominantly hydro – generating plants.

(ii) A single control area consisting of predominantly steam/gas powered generating plants.

(iii) Two interconnected areas with one area consisting of predominantly hydro- generating plants and the other consisting of steam /gas generating plants.

Reports in the technical literature, so far, show that most investigators assume first order perturbations. Therefore simulations had been limited to the incremental linear model dynamics of the power system load – frequency interaction [4,6]. Given the observed characteristics (wide variations in load/generation demand) of the Nigeria power system, results based on the incremental linear models may prove unsatisfactory for purpose of sound engineering decision making.

In this paper therefore, the load is allowed to vary widely while the system is under integral control action. First order perturbations are also imposed on the system and the excursions of frequency and accelerating power observed in both situations. For the two-area interconnection, the disturbances are allowed to occur in one area at a time with a record of the tie-line variation added to the former. The choice of an integral controller is informed by the fact that conventional AGC equipment contains controllers of that class.

## 2.0 EQUIVALENT LINEAR FORMS OF THE DERIVED SUB-MODELS

In order to synthesize an automatic generation control (AGC) scheme for each of the three different models of the Nigerian power system, the linear forms of the derived equations are needed. These linearised equations are presented below as components transfer functions.

## 2.1 HYDRO GOVERNING SYSTEM

If in part I, the hydro generating unit is operated at a given steady-state condition below the rated output and the change in load demand is assumed to be small so that the constraints on gate opening position g and its velocity $\breve{g}$ do not exist, then, an incremental change $\Delta G$ in the governor – controlled gate position will result. Taking the Laplace transform of the hydro-governing equations derived in part I yields

$$sc_h = sb - rsg - \frac{1}{T_R}(ch + b) \qquad (1a)$$

$$Sg = \phi_h c_h - \phi_h Rg \qquad (1b)$$

where all the parameters are as defined in part I. Now solving for $c_h$ in eqn.(1b), substituting in (1a) and rearranging gives,

$$g\left(s^2 + s(\phi_h R + \phi_h r + \frac{1}{T_R}) + \phi_h R \frac{1}{T_R}\right) = \phi_h b(s + \frac{1}{T_R}) \qquad (2)$$

The quadratic term in the square bracket above is solved to give two approximate roots

$$s_1 = -\frac{1}{T_R} \text{ and } s_2 = \phi_h R + \phi_h r = \frac{r}{R}\phi_h\left(\frac{R^2}{r} + R\right)$$

which are substituted in equation (2) to obtain

$$g\left((s + \frac{1}{T_R})(s + [\phi_h R + \phi_h r])\right) = \phi_h (s + \frac{1}{T_R})b \qquad (3)$$

Since the bracketed term in $s_2$ is a constant for any given setting of r and R , the relationship between the speed changer signal $\Delta p_c$ , the frequency feedback signal $\Delta f$ and the change in gate position DG is given by the transfer function

$$\Delta G = \frac{sT_R + 1}{(ST_G + 1)(r/RsT_R + 1)}(\Delta P_c - \frac{1}{R}\Delta f) \qquad (4)$$

where

$\Delta G$ is change in governor controlled gate position.

$T_G = \frac{1}{\phi_h R + \phi_h r}$ is the hydro-turbine governor time constant

R is steady – state speed regulation.

r is transient speed regulation.

$\Delta P_c$ is change in the speed changer (AGC) signal.

The variable b has been replaced by $\Delta P_c$ - $1/R \Delta f$ as derived in part I.

## 2.2 Steam Governing System

By following similar arguments as above and starting form the explicit form of the steam-turbine governing model derived in part I, it is also shown that the linearised model of the steam governing mechanism is given as

$$\Delta G = \frac{1}{sT_G + 1}\left(\Delta P_c - \frac{1}{R}\Delta f\right) \qquad (5)$$

Where all the parameters are as defined above.

## 2.3 Hydro – turbine Dynamics

In deriving the linearised model of the hydro – turbine dynamics, the effect of servo control on the turbine blades is neglected and the turbine is assumed to be operating within the linear range so that neither turbulence nor compressibility exists. It is further assumed that the velocity of water varies directly with the gate opening and with the square root of the net head [ ]. Hence the velocity of the water in the turbine and the conduit is given by

$$V = K G \sqrt{H_T} \qquad (6)$$

Where G is the fractional gate opening;

$H_T$ is the effective head of water;

V is the instantaneous velocity and

K is the constant of proportionality.

For small displacements from an equilibrium position, eqn. (6) is differentiated to obtain:

$$\frac{\Delta v}{v_o} = \frac{1}{2}\frac{\Delta H}{H_R} + \frac{\Delta G}{G} \qquad (7)$$

where $H_R$, $v_o$ and G are the nominal head, velocity and fractional gate opening respectively. By Newton's second law, the acceleration due to the change in head at the turbine may be expressed as:

$$\rho LA \frac{d(\Delta v)}{dt} = -A\rho g_v \Delta H \qquad (8)$$

where $\rho$ is the mass density of water

A is the cross-sectional area of the pipe

$g_v$ is the acceleration due to gravity and

L is the length of the conduit.

$\rho LA$ is the mass of water in the conduit while $\rho g_v \Delta H$ is the incremental increase in pressure at the turbine. In normalised form, eqn. (8) becomes

$$\frac{Lv_o}{g_v H_R} s \left(\frac{\Delta v}{v_o}\right) = -\left(\frac{\Delta H}{H_R}\right) \qquad (9)$$

where s = d/dt is the Laplace operator and $s\,\Delta v/v_o$ is the normalised acceleration. Now the coefficient of the normalised acceleration can be expressed as a nominal starting time $T_w$ so that

$$T_w = \frac{Lv_o}{g_v H_R} \qquad (10)$$

The nominal starting time is the time required for a head $H_R$ to accelerate the water in the conduit from standstill to the velocity $v_o$. By solving eqn. (7) for $[\Delta H/H_R]$ and substituting the result in eqn. (9), an expression relating the change in velocity to the change in gate opening is obtained as

$$\frac{\Delta v}{v_o} = \frac{1}{\frac{T_w}{2}s + 1} \frac{\Delta G}{G} \qquad (11)$$

where $T_w$ in eqn. (10) has been used.

The output of the turbine may be expressed as

$$P_m = (\text{pressure})(\text{flow}) = K_2 H_v \qquad (12)$$

Where $K_2 = \rho^2 LAg_v$ is a constant.
Differentiating eqn. (12) yields

$$\frac{\Delta p_m}{p_m} = \frac{\Delta H}{H_R} + \frac{\Delta v}{v_o} \qquad (13)$$

By substituting eqn.(9) for $[\Delta H/H_R]$ and (11) for $[\Delta v/v_o]$ into eqn. (13), the transfer function for turbine output is found as a function of gate position viz:

$$\frac{\Delta p_m}{p_m} = -\frac{T_w s + 1}{\frac{T_w}{2}s + 1} \frac{\Delta G}{G} \qquad (14)$$

By expressing the values in per unit and noting that the turbine power $p_m$ is directly proportional to the generated power $P_G$, eqn. (14) can be written as

$$\Delta P_G = \frac{-sT_w + 1}{s(T_w/2) + 1} \Delta G \qquad (15)$$

where

$\Delta P_G$ is change in generated power proportional to turbine power.

$\Delta_G$ is change in governor controlled gate position.

$T_w$ is water starting time in seconds.

### 2.4 Steam-Turbine Dynamics

The model of the steam turbine dynamics derived in part I is given by

$$\Delta P_G = \frac{1 + F_1 sT_{rh}}{(1 + sT_{rh})(1 + sT_{cH})} \Delta G \qquad (16)$$

where $\Delta P_G$ and $\Delta G$ are as defined above:

$T_{cH}$ is time constant of the chest and high pressure piping

$T_{rh}$ is reheat time constant

$F_1$ is output efficiency of the high-pressure chamber

This equation is already linearised and can therefore be used directly.

### 2.5 Power Transmission System Model.

The linearised model of the power transmission system has been derived in part I as

$$[\Delta P_{Gi}(s) - \Delta P_{Di}(s) - \Delta P_{Ei}(s)]G_{pi}(s) = \Delta f_i(s) \qquad (17)$$

where

$$G_{pi}(s) = \frac{k_{pi}}{1 + sT_{pi}}$$

$$k_{pi} = \frac{1}{D_i} \text{ Hz /pu Mw}$$

and

$$T_{pi} = \frac{2H_i}{f_o D_i} \text{ seconds}$$

All the parameters have been defined in part I. Note that for a single control area, $\Delta P_{Ei} = 0$

### 2.6 Power System Stabilizer.

It is conventional in power system operations to feedback a signal proportional to the integral of the frequency deviation for the purpose of zeroing the frequency error [68]. Usually, this signal is fed to the secondary control equipment. In this thesis, the above condition is achieved by passing the frequency error signal through an ideal integrator having a normalised gain of unity. If the resulting signal is represented by

$$\Delta P_z = \frac{1}{s}\Delta f \qquad (18)$$

where 's' is Laplace operator.

For an interconnected power system, the integral of the tie-line power error signal is also added, hence

$$\Delta P_z = \frac{1}{s}\left(k_f \Delta f + \Delta P_E\right) \qquad (19)$$

where $\Delta P_E$ is the tie-line power deviation and $k_f$ is the frequency bias.

## 3.0 Complete System Models

In this subsection, the corresponding component equations derived above are appropriately combined to form each of the proposed AGC models of the Nigerian power system. Each model is represented by a state equation of general form,

$$X(t) = Ax(t) + Bu(t) + P\xi(t) \qquad (20)$$

Where $x \varepsilon \Re^n$, $u \varepsilon \Re^m$, $\xi \varepsilon \Re^p$, $A \varepsilon \Re^{nxn}$, $B \varepsilon \Re^{nxm}$ and $P \varepsilon \Re^{nxp}$. The vector x represents the n-states of the system, u is an m-vector of control inputs while $\xi$ is a p-vector of disturbances. The constant matrices A, B and P, which define the nominal linear system, represent the nxn system matrix, the nxm control matrix and the nxp disturbance matrix respectively. The elements of the matrices A, B and P are computed from the known characteristics of the power system.

### 3.1 The Model Of The Hydro-Dominated Single Control Area

The complete power system model for the hydro-dominated single control area is obtained by combining eqn.(4) for the hydro – governing mechanism with eqn.(15) for the hydro – turbine dynamics, eqn.(17)for the power transmission network (where $\Delta P_E = 0$) and eqn.(18) for the power system stabilizer. The result of this combination is represented in the block diagram of fig. 1.

### 3.2 The Model of A Single – Control Area Dominated By Steam – Powered Plants.

Similar to the above procedure, equation (5) representing the governing system dynamics for the steam plant is combined with eqn. (16) for the steam – turbine, for the power system stabilizer to obtain the complete system model for a single control area dominated by steam-powered generators. The block diagram of fig.2 shows clearly the result of this combination.

### 3.3 The Model of The Two-Area Interconnection

The two-area interconnection described here consists of one hydro – dominated area and another area, which is dominated by steam – powered generating plants. Thus, the model of the interconnected area is obtained by combining the two single – area models derived above such that $DP_E$ is retained in eqn.(17) for the power transmission system while eqn.(19) is inserted to represent the power system stabilizer. The resulting block diagram representation of the model is depicted in fig.3a.

## 4.0 Simulation Studies Of The Plant Response

In this section, the response of the proposed models of the Nigerian power system to various head demand changes is investigated. The aim is to determine the suitability of the integral controller as a possible automatic generation control scheme for the Nigerian power system. The integral control signal 'u' (see block diagrams) act on the speed changers of electric generators to effect generation control.

### 4.1 Hydro-Dominated Single Area Model

The system depicted by the block diagram of fig.1 can be represented in the **state** space form of eqn.(20) if:

$$A = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & \frac{-1}{T_p} & \frac{k_p}{T_p} & 0 & 0 \\ 0 & 0 & \frac{-2}{T_w} & \frac{-2}{T_G} & \frac{2}{T_w} + \frac{2}{T_G} \\ 0 \quad \frac{1}{k_i R T_p} & -\frac{1}{k_i R T_R} & \frac{-kp}{k_i R T_p} & \frac{-1}{k_i T_R} & 0 \\ 0 & 0 & 0 & \frac{1}{T_G} & -\frac{1}{T_G} \end{pmatrix} \tag{21}$$

$$B = \begin{pmatrix} 0 & 0 & 0 & \frac{1}{k_i T_R} & 0 \end{pmatrix}^T \tag{22}$$

$$\Gamma = \begin{pmatrix} 0 & -\frac{k_p}{T_p} & 0 & \frac{kp}{k_i R T_p} & 0 \end{pmatrix}^T \tag{23}$$

The superscript T denotes vector or matrix transpose. By substituting for the parameter values of the Nigerian power system (see appendix A), eqn. 20 – 22 become

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & -1415 & 4.7169 & 0 & 0 \\ 0 & 0 & -0.5 & -3.33 & 3.83 \\ 0 & 6.925 & -4.718 & 0 & -0.0209 \\ 0 & 0 & 0 & 1.667 & -1.667 \end{bmatrix} \tag{24}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0.0209 & 0 \end{bmatrix}^T \tag{25}$$

$$\Gamma = \begin{bmatrix} 0 & -4.7169 & 0 & 4.7169 & 0 \end{bmatrix}^T \tag{26}$$

### 4.2 Steam – Dominated Single Area Model

The block diagram of a single control area dominated by steam – powered electric generators is shown in fig.2. this system can be modelled in the state variable form of eqn.20, if :

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 1 & -\frac{1}{T_G} & -\frac{1}{T_G^{R}} & 0 & 0 \\ 0 & 0 & \frac{-1}{T_p} & \frac{k_p}{T_p} & 0 \\ 0 & 0 & 0 & -\frac{1}{T_{ch}} & \frac{1}{T_{ch}} \\ 0 & \frac{1}{T_{ch}} - \frac{F_1}{T_G} & \frac{-F_1}{T_G^{R}} & 0 & \frac{1}{T} \end{bmatrix} \qquad (27)$$

$$B = \begin{bmatrix} 0 & \frac{1}{T_G} & 0 & 0 & \frac{F_1}{T_G} \end{bmatrix}^T \qquad (28)$$

$$\Gamma = \begin{bmatrix} 0 & 0 & \frac{k_p}{T_p} & 0 & 0 \end{bmatrix} \qquad (29)$$

### 4.3 Model For A Two – Area Interconnection

The block diagram representation of a two-area interconnection is shown in fig.3.subsystem I is dominated by hydro-generating plants while subsystem j is controlled by steam powered electric generators. Each area is assumed to be autonomous from the point of view of supplying its own load under normal operating conditions. When there occurs a load variation, resulting in deviations in frequency and scheduled tie – line power, the AGC equipment first detects whether the load variation is in its own area or in the neighbouring area. The AGC equipment reacts only if the load variation is in its own area.

Against the above background, the block diagram of fig.3 can be said to be inherently decoupled. It can therefore, be represented in the state variable form of eqn.(20) as a weakly coupled set of two subsystems viz :

$$x_e(t) = A_e x_e(t) + B_e u_e(t) + \Gamma_e \xi_e(t) \qquad (30)$$

where

$x_e = [x_i, x_j]$ is the state vector

$u_e = [u_i, u_j]$ is the control vector

$x_e = [\xi_i, \xi_j]$ is the disturbance vector

$x_i$ = is the state vector of subsystem i

$u_i$ = is the control input vector of subsystem i and

$x_i$ = is the disturbance vector of subsystem i.

The matrix $A_e$, $B_e$ and $\Gamma_e$ are constant matrices defined as

$$A_e = \left[\begin{array}{c|c} A_{ii} & A_{ij} \\ \hline A_{ij} & A_{jj} \end{array}\right]$$

Where $A_{ii}$ , $A_{jj}$ are the system matrices of subsystems i and j respectively while $A_{ij}$ , $A_{ij}$ are the respective intersection matrices ;

$$B_e = [B_i, B_j]$$

$$\Gamma_e = [\Gamma_i, \Gamma_j]$$

where $B_i$ , $\Gamma_i$ are the control and disturbance matrices of subsystem i while $B_j$ , $\Gamma_j$ are those of subsystem j.

The block diagram of fig.3 can be reduced to the equation of eqn.(30) if :

$$A_{ii} = \begin{pmatrix} 0 & k_{fi} & 1 & 0 & 0 & 0 \\ 0 & \frac{-1}{T_{pi}} & -\frac{k_{pi}}{T_{pi}} & \frac{k_{pi}}{T_{pi}} & 0 & 0 \\ 0 & 0 & T_{ij} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{-2}{T_{\omega}} & \frac{2}{T_{\omega}} + \frac{2}{T_{Gi}} & -\frac{2}{T_{Gi}} \\ 0 & 0 & 0 & 0 & \frac{-1}{T_{Gi}} & \frac{1}{T_{Gi}} \\ 0 & \left(\frac{1}{k_t R_i T_{pi}} - \frac{1}{k_t T_R R_i}\right) \frac{kpi}{k_t R_i T_{pi}} & & \frac{-kpi}{k_t R_i T_{pi}} & 0 & \frac{1}{k_t T_R} \end{pmatrix} \qquad (31)$$

$$A_{ij} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & T_{ij} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \qquad (32)$$

$$A_{jj} = \begin{pmatrix} 0 & 1 & k_{i2} & 0 & 0 & 0 \\ 0 & -\frac{1}{T_{Gj}} & 0 & \frac{1}{R_j T_{Gj}} & 0 & 0 \\ 0 & 0 & -\frac{k_{pj}}{T_{pj}} & -\frac{1}{T_{pj}} & \frac{k_{pj}}{T_{pj}} & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_{ch}} & -\frac{1}{T_{ch}} \\ 0 & \left(\frac{1}{T_{rh}} - \frac{F_1}{T_{Gj}}\right) & 0 & -\frac{F_1}{R_j T_{Gj}} & 0 & -\frac{1}{T_{rh}} \end{pmatrix} \qquad (33)$$

$$A_{ji} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -a_{ij}T_{ij} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \qquad (34)$$

$$B_i = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad \frac{1}{k_t T_R}]^T \qquad (35)$$

$$B_j = [0 \quad \frac{1}{T_{Gj}} \quad 0 \quad 0 \quad 0 \quad \frac{F_1}{T_{Gj}}]^T \qquad (36)$$

$$\Gamma_i = [0 \quad -\frac{k_{pi}}{T_{pi}} \quad 0 \quad 0 \quad 0 \quad \frac{k_{pi}}{k_t T_{pi} R_i}]^T \qquad (37)$$

$$\Gamma_j = [0 \quad 0 \quad 0 \quad -\frac{k_{pj}}{T_{pj}} \quad 0 \quad 0]^T \qquad (38)$$

By substituting for the parameter values of the Nigerian power system (see Appendix A), eqns.(31) to (38) reduce to :

$$A_{ii} = \begin{pmatrix} 0 & 0.15 & 1.0 & 0 & 0 & 0 \\ 0 & -0.1415 & -4.717 & 4.717 & 0 & 0 \\ 0 & 0.1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.5 & 3.83 & -3.33 \\ 0 & 6.925 & 4.718 & -4.718 & 0 & -0.0236 \\ 0 & 0 & 0 & 0 & -1.667 & 1.667 \end{pmatrix}$$

$$A_{ij} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$$A_{jj} = \begin{pmatrix} 0 & 1 & 0.53 & 0 & 0 & 0 \\ 0 & -10 & 0 & -5 & 0 & 0 \\ 0 & 0 & 0 & 0.1 & 0 & 0 \\ 0 & 0 & -4.718 & -0.1415 & 4.718 & 0 \\ 0 & 0 & 0 & 0 & -3.846 & 3.846 \\ 0 & -4.9 & 0 & -2.5 & 0 & -0.1 \end{pmatrix}$$

$$Aji = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$B_i = [0 \quad 0 \quad 0 \quad 0 \quad 0.236 \quad 0]^T$

$B_j = [0 \quad 10 \quad 0 \quad 0 \quad 0 \quad 5]^T$

$G_i = [0 \quad -4.718 \quad 0 \quad 0 \quad -4.717 \quad 0]^T$

$G_j = [0 \quad 0 \quad 0 \quad -4.718 \quad 0 \quad 0]^T$

## 4.4 DISCUSSION OF RESULTS

Figures 4 to 7 represent the simulation results of the respective models of the power system for load variations of 0.06pu and 0.1pu (i.e. small and wide variation). It is clear that for 1st order load perturbations, the performance of the system in terms of percent overshoot, settling time and steady state error of the frequency, generation and tie-line deviation could be said to be acceptable. However, for wide variation in load due largely to component failures, the system hardly settles. Such continous oscillation will cause system collapse. It can therefore be concluded that the conventional AGC equipment incorporating a proportional plus integral (PI) controller is not very suitable for Nigeria. An improved control scheme is needed to compliment the PI strategy.

## 5. CONCLUSION

This paper has proposed three possible operating strategies for the Nigerian power system, which will enhance the incorporation of an appropriate AGC scheme into the system structure. The proposed models were then used to experiment on the suitability of the conventional AGC scheme in the industry, which is a proportional plus integral control action. It was observed that the system under PI control action performed acceptably when the load perturbation is first order but failed woefully when the load change is of the order of 0.1 pu. Given the Nigerian power system, which is characterised by sudden wide variations in load, it becomes clear that the PI controller is not suitable for the Nigerian system.

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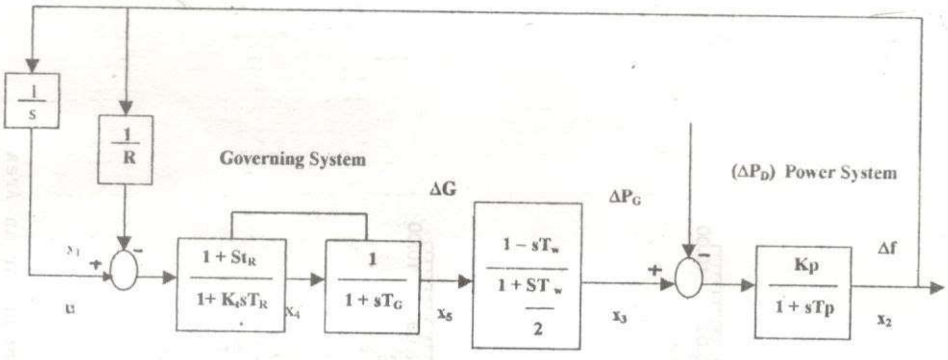



Fig. 1– Block Diagram of A Hydro – Dominated Area with Integral Controller

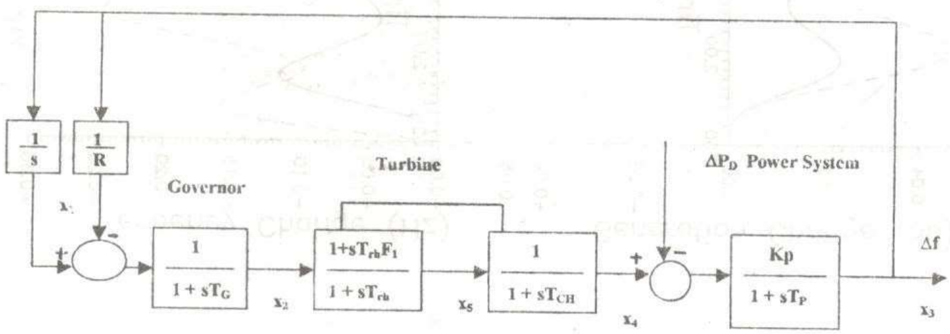



Fig. 2 – Block Diagram of Steam – Dominated Area with Integral Controller

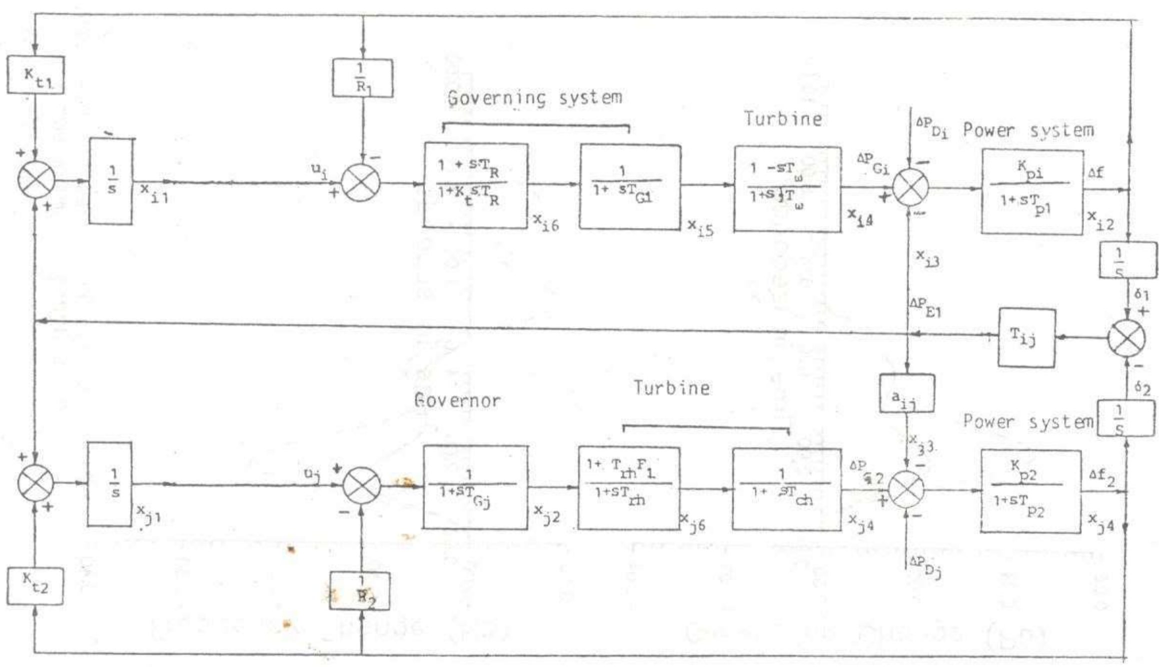



Fig: 3 - Block Diagram of an Interconnected Area with integral Controller

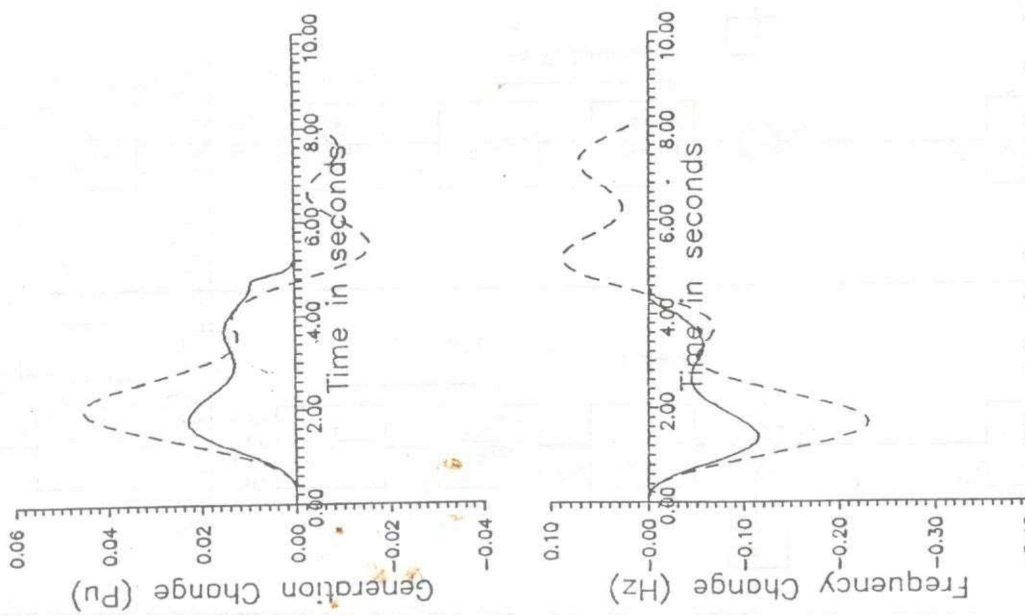
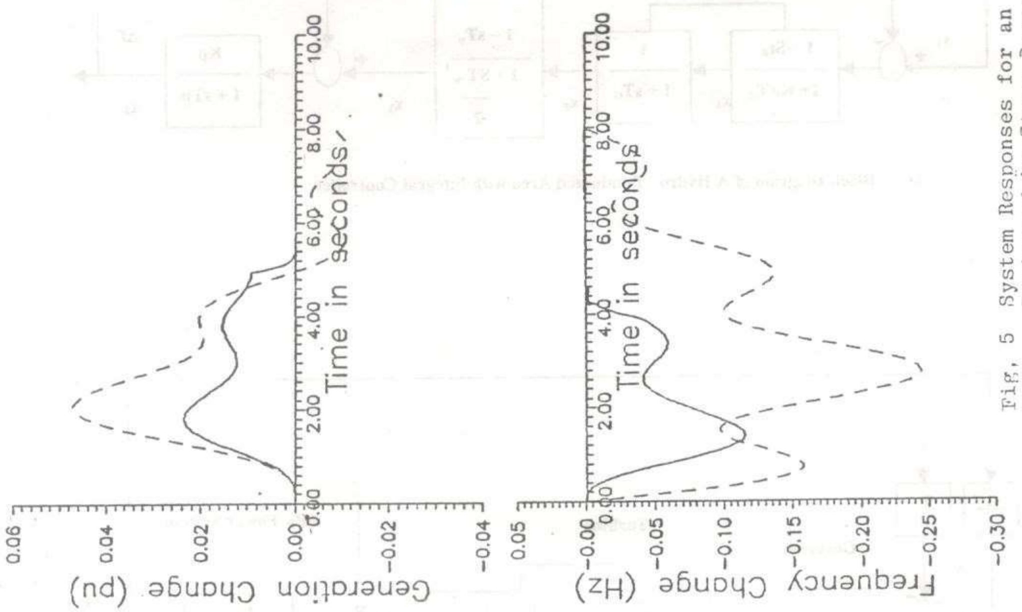



Fig. 4 System Responses for D = 0.75, R = 04pu For a Hydro - Dominated Area.

— Smal Variation

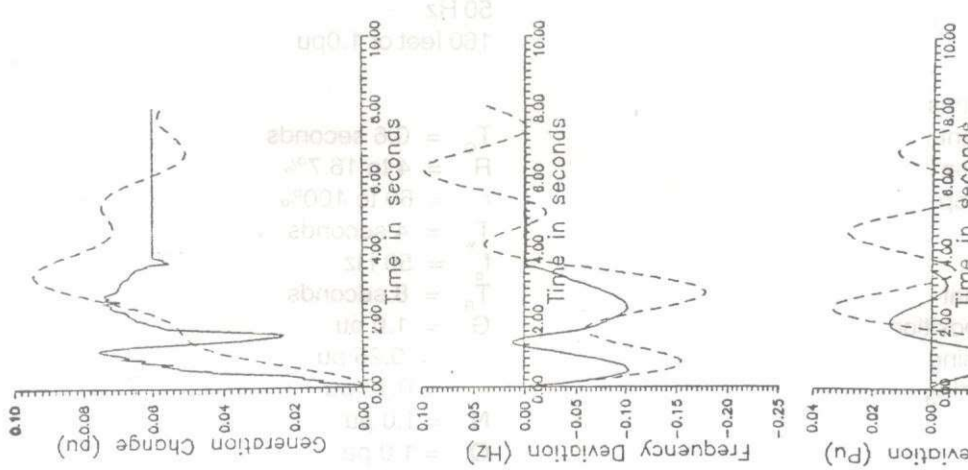
--- Wide Variation




Fig, 5 System Responses for an Area Dominated by Steam Powered Plants with D = 0.75, K = 0.04pu

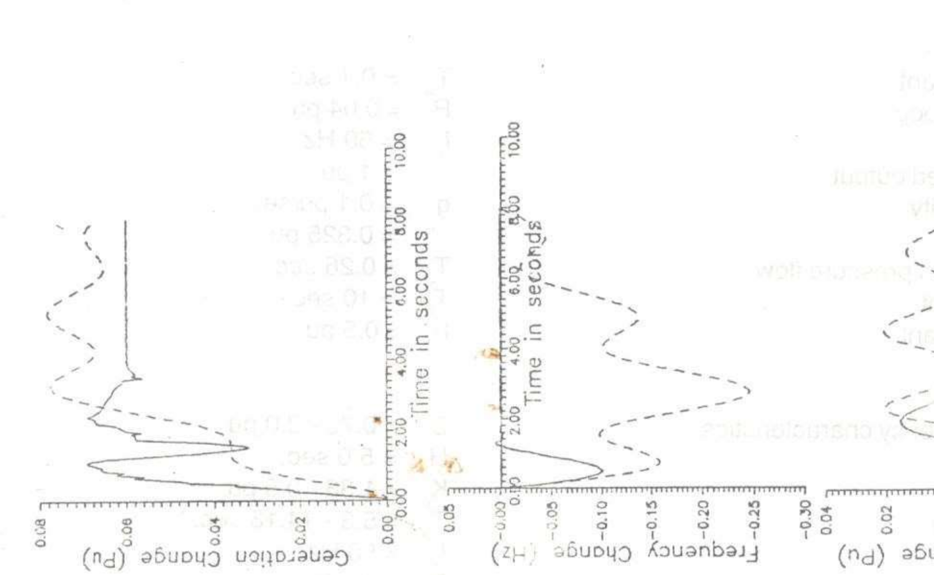
— Small Variation

--- Wide Variation




Fig, 7 System Responses in area j for load variation in area j

—— Small variation
--- Wide variation.




Fig, 6 System Responses in area i for load Variation in area i.

—— Small Variation
--- Wide Variation

## APPEDIX A

## PARAMETER VALUES OF THE NIGERIAN POWER SYSTEM

| | | |
|---|---|---|
| | Hydro - units 7 & 8 at Kainji power station. | |
| | Rated output MVA in continous service | 85.000 MVA |
| | Power Factor | 0.94 |
| | Rated Output Mw (approx) | 80.000Mw |
| | Voltage rating | 16kv |
| | Current rating | 3070 A |
| | No of poles | 52 |
| | Speed | 115.4 r.p.m. |
| | Frequency | 50 Hz |
| | Rated Head ($H_T$) | 160 feet or 1.0pu |
| | Model Parameter Values | |
| | Governor time constant | $T_G$ = 0.6 seconds |
| | Parameter speed droop | R = 4 to 16.7% |
| | Temporary speed droop | r = 60 to 100% |
| | Water starting time | $T_w$ = 4 seconds |
| | Nominal frequency | $f_o$ = 50 Hz |
| | Washout time constant | $T_R$ = 8 seconds |
| | Rated gate opening position | G = 1.0 pu |
| | $\phi h$ at rated gate opening | = 0.25 pu |
| | $C_h$ at rated gate opening | = 0.15 pu |
| | Rated blade velocity | N = 1.0 pu |
| | Rated turbine flow | Q = 1.0 pu |
| | Rated gate opening velocity | g = 0.1pu/sec. |
| | Maximum gate opening velocity | $g_{max}$ = 0.2 pu/sec. |
| | Minimum blade angle | $\phi_{Bmin}$ = 0.349 rad |
| | Blade servo time constant | $T_B$ = 0.08 second |
| II | Steam Powered Generating Station (Egbin) | |
| | Rated MVA | 245.8 MVA |
| | Power Factor | 0.9 |
| | Rated Real power | 221.2 MVA |
| | Voltage Rating | 16 kv |
| | Speed 9 Nominal | 3000 r. p.m. |
| | Model parameters - | |
| | Governor time constant | $T_G$ = 0.1 sec. |
| | Permanent speed droop | R = 0.04 pu |
| | Nominal frequency | $f_o$ = 50 Hz |
| | Valve opening at rated output | = 1 pu |
| | Valve opening velocity | g = 0.1 pu/sec. |
| | $\phi_3$ at rated output | = 0.325 pu |
| | Time constant of high pressure flow | $T_{cH}$ = 0.26 sec. |
| | Reheat time constant | $T_{rh}$ = 10 sec. |
| | High pressure constant | $F_1$ = 0.5 pu |
| III | General Grid Data | |
| | Inherent load - frequency characteristics | D = 0.75 - 2.0 pu |
| | Inertia constant | H = 5.0 sec. |
| | Model gain | $K_p$ = 1.33 - 0.5 pu |
| | Model time constant | $T_p$ = 5.3 - 14.13 sec. |
| | Nominal frequency | $f_o$ = 50 Hz |
| | Scheduled tie - line power | $P_E$ = 0.1 pu |