DESIGN OF STATE SPACE MODEL AND OPTIMAL CONTROLLER FOR AUTOMATIC GENERATION CONTROL OF TWO AREA THERMAL POWER SYSTEM

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ABSTRACT

Automatic generation control is a basic control mechanism in power system operation. Whenever there is a variation in load demand on a generating unit momentarily, there is an occurrence of unbalance between real power input and output. This difference is being supplied by the stored energy of the rotating parts of the units. A large power system can be divided into a number of load frequency control areas interconnected by tie-lines. The control objective is to regulate the frequency of each area and to simultaneously regulate the power flow through the tie-line according to an inter area power agreement. The overall control mechanism is very complex and of higher order nonlinear dynamics. The state-space concept is a very useful for analyzing such kind of control mechanisms. This paper illustrates how to incorporate state-space concept in automatic generation control and design controller in state variable form for two-area thermal power system.

Keyword: *Automatic generation control, load frequency control, state space analysis, state –variable form, two area system, optimal control.*

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1. INTRODUCTION:

In a power system, both active and reactive power demands are never steady and they continually change with rising or falling trend. Steam input to turbo generators or water input to hydro-generators must, therefore, continuously regulated to match the active power demand, falling which the machine speed will vary with consequent change in frequency and it may be highly undesirable. Generally, the maximum permissible change in frequency is ±2%. Also, the excitation of the generators must be continuously regulated to match the reactive power demand with reactive power generation; otherwise, the voltages at various buses of the system may violate the prescribed limits. In modern large interconnected systems, manual regulation is not feasible and therefore automatic generation control mechanism and voltage regulation equipment is installed on each generator. The controllers are set for a particular operating condition and they take care of small changes in load demand without exceeding the limits of frequency and voltage. As the change in load demand becomes large the controllers must be reset either manually or automatically. [1]

The three main objectives of Automatic Generation Control (AGC) include:

- Sustaining frequency as close to nominal as possible to the specified range
- Maintenance of appropriate level of interchange power
- Maintenance of economic generation of each unit

The main route of implementation of the AGC involves usage of a central location. The premise is to telemeter the information from that central location. The regulation is done digitally and the same telemetry channels are used for transmission. [1] The necessary information can include:

- Unit megawatt output for all committed units
- Megawatt flow (neighboring systems)
- System frequency

This being described, it is also imperative to know what criteria would constitute a good AGC system:

- The ACE signal must be kept in check from becoming too large. The load variation has a direct effect on the ACE and thus the standard deviation values should be minimal.
- There should be no drifting of the ACE. This is important because if the drifting occurs then we can have the issue of inadvertent interchange errors. By a minimal drift, the meaning being implied is that the integral of Ace should be small.
- The control action values of AGC should be small and kept that way. For instance, you can have random load changes which shouldn't cause control action. The objective is also to be able to monitor intelligently. In this way, the system is able to regulate those events/processes which are necessary rather than the random ones which have no effect. [1]

2. STATE-SPACE ANALYSIS:

State space analysis is a very useful technique of analyzing control systems. It is based on the concept of state and applicable to linear, non-linear, time invariant, time varying, single-inputs single-outputs (SISO) as well as multiple-inputs multiple-outputs (MIMO) control systems. [2]
In classical method of control system analysis, the Laplace transform method is applied to obtain the transfer function model representing linear, time invariant system. This method provides a practical approach for the design and analysis of feedback control systems. The graphical methods such as root locus, bode plot, nyquist plot, polar plot etc. are based on transfer function model. The initial conditions imposed on the variable need not be considered here. However, the transfer function approach for the analysis of feed-back control systems has some drawbacks:

- Transfer function model is defined under zero initial conditions.
- This approach is applicable only to linear time invariant systems.
- The model based on transfer function approach is applicable to single input single output systems.
- The analysis using the graphical techniques such as root-locus, frequency response etc. is based on trial and error procedure and hence less accurate.
- The information regarding the internal variables of a system is not derivable.

Due to these limitations of transfer function method, the state variable approach is developed. The state space analysis involves the description of the system in terms of n^{th} order differential equations by selecting appropriate variables known as state variables. These variables are independent of each other and initial conditions of the variables can also be incorporated for the analysis. State space approach has the following advantages:

- The state space approach is applicable to linear, non-linear, time variant and time invariant systems.
- The initial conditions of the system variables can be incorporated for analysis.
- Any differential equation of n^{th} order can be considered for analysis which is not possible in any other methods.
- It is easier to apply where the Laplace transform cannot be applied.
- It is a time domain approach and suitable for digital computer computation.
- This approach can be applied in optimal design and control of a system with respect to given performance index.

The state space approach does not completely replace the classical transfer function method. The transfer function approach gives preliminary insight into physical nature of a system which helps in designing the system.

3. STATE-SPACE MODEL FOR AUTOMATIC GENERATION CONTROL (AGC):

A modern gigawatt generator with its multistage reheat turbine, including its automatic load frequency control(ALFC) and automatic voltage regulator (AVR) controllers, is characterized by an impressive complexity. When all its non- negligibility dynamics are taken into account, including cross coupling between control channels, the overall dynamic model may be of the twentieth order. In order to obtain more satisfactory control, optimal control theory has to be used. For this purpose, the power system model must be in state-space model. [1] [3]

The dimensionality barrier can be overcome by means of computer aided optimal control design methods originated by Kalman. A computer –oriented technique called Optimum Linear regulator(OLR) design has proven to be particularly useful in this regard.

The OLR design results in a controller that minimizes both transient variable excursions and control efforts. In terms of power system, this means optimally damped oscillation with minimum wear and tear control valves. [4]

OLR can be designed using the following steps:

- (i) Casting the system dynamic model in state variable model in state –variable form and introducing appropriate control forces.
- (ii) Choosing an integral –squared –error control index, the minimization of which is the control goal.
- (iii) Finding the structure of the optimal controller that will minimize the chosen control index.

4. STATE SPACE MODEL OF TWO AREA THERMAL (REHEAT) POWER SYSTEM:

The state variables are a minimum set of variables which contain sufficient information about the past history with which all future states of the system can be determined for known control inputs. The state space model of two area thermal (reheat) power system, with full state feedback (11 state feedback) has been developed as shown in Fig.1

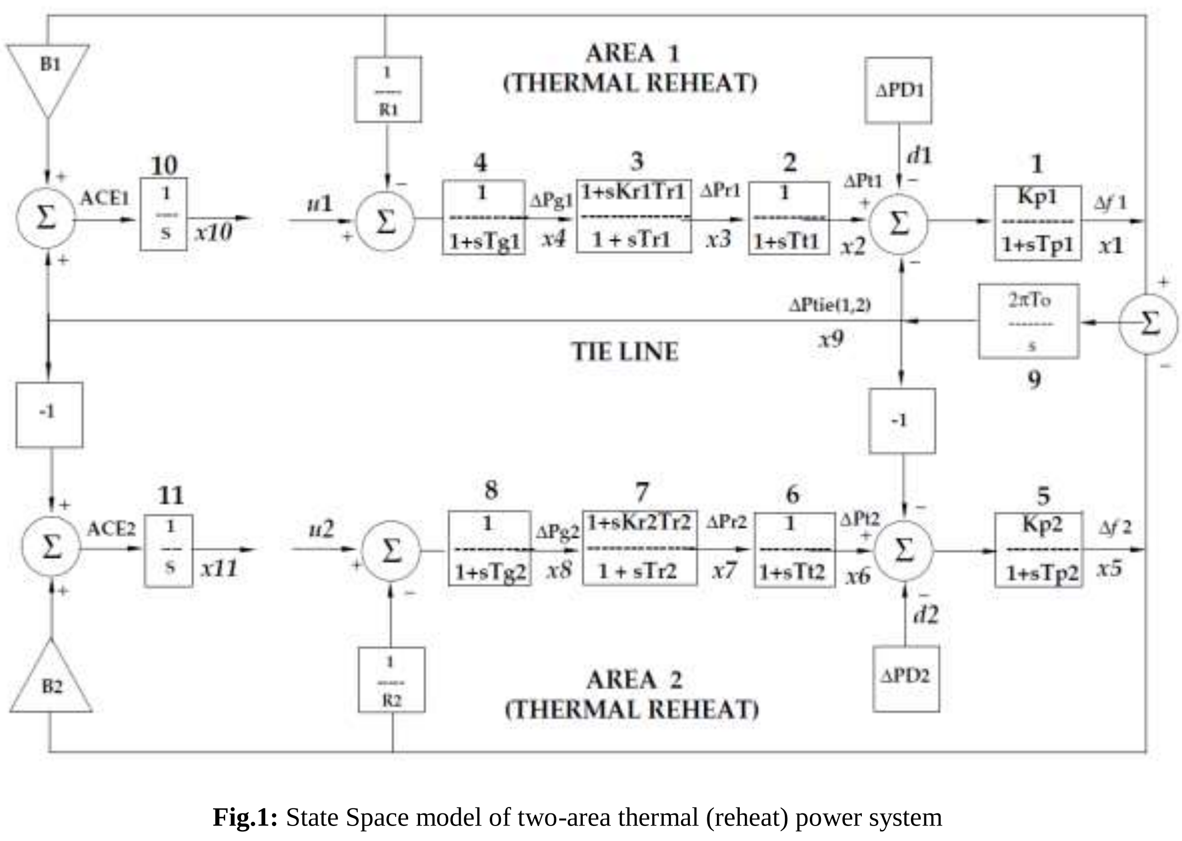

Fig.1: State Space model of two-area thermal (reheat) power system

For the two area system,

State variables:

Area-1	Area-2
$x_1 = \Delta f_1$	$x_5 = \Delta f_2$
$x_2 = \Delta Pt_1$	$x_6 = \Delta Pt_2$
$x_3 = \Delta Pr_1$	$x_7 = \Delta Pr_2$
$x_4 = \Delta Pg_1$	$x_8 = \Delta Pg_2$
$x_{10} = \int ACE_1 dt$	$x_{11} = \int ACE_2 dt$
$x_9 = \Delta P_{tie(1,2)}$	

Control inputs: u_1 for area-1 and u_2 for area-2

Disturbance inputs: $d_1 = \Delta P_{D1}$ and $d_2 = \Delta P_{D2}$

State equations:

For Block 1:

$$x_1 + T_{P1}\dot{x}_1 = K_{P1}(x_2 - x_9 - d_1)$$
$$\text{i.e., } \dot{x}_1 = -\frac{1}{T_{P1}}x_1 + \frac{K_{P1}}{T_{P1}}x_2 - \frac{K_{P1}}{T_{P1}}x_9 - \frac{K_{P1}}{T_{P1}}d_1$$

For Block 2:

$$x_2 + Tt_1\dot{x}_2 = x_3$$
$$\text{i.e., } \dot{x}_2 = -\frac{1}{Tt_1}x_2 + \frac{1}{Tt_1}x_3$$

For Block 3:

$$x_3 + Tr_1\dot{x}_3 = x_4 + Kr_1 Tr_1 \dot{x}_4$$
$$\text{i.e., } \dot{x}_3 = -\frac{1}{Tr_1}x_3 + \frac{1}{Tr_1}x_4 + Kr_1\left(\frac{-1}{R_1 Tg_1}x_1 - \frac{1}{Tg_1}x_4 + \frac{1}{Tg_1}u_1\right)$$
$$\text{i.e., } \dot{x}_3 = -\frac{Kr_1}{R_1 Tg_1}x_1 - \frac{1}{Tr_1}x_3 + \left(\frac{1}{Tr_1} - \frac{Kr_1}{Tg_1}\right)x_4 + \frac{Kr_1}{Tg_1}u_1$$

For Block 4:

$$x_4 + Tg_1\dot{x}_4 = \frac{-1}{R_1}x_1 + u_1$$
$$\text{i.e., } \dot{x}_4 = \frac{-1}{R_1 Tg_1}x_1 - \frac{1}{Tg_1}x_4 + \frac{1}{Tg_1}u_1$$

For Block 5:

$$x_5 + T_{P2}\dot{x}_5 = K_{P2}(x_6 + x_9 - d_2)$$
$$\text{i.e., } \dot{x}_5 = -\frac{1}{T_{P2}}x_5 + \frac{K_{P2}}{T_{P2}}x_6 + \frac{K_{P2}}{T_{P2}}x_9 - \frac{K_{P2}}{T_{P2}}d_2$$

For Block 6:

$$x_6 + Tt_2\dot{x}_6 = x_7$$
$$\text{i.e., } \dot{x}_6 = -\frac{1}{Tt_2}x_6 + \frac{1}{Tt_2}x_7$$

For Block 7:

$$x_7 + Tr_2\dot{x}_7 = x_8 + Kr_2Tr_2\dot{x}_8$$
$$\text{i.e., } \dot{x}_7 = -\frac{1}{Tr_2}x_7 + \frac{1}{Tr_2}x_8 + Kr_2\left(-\frac{1}{R_2Tg_2}x_5 - \frac{1}{Tg_2}x_8 + \frac{1}{Tg_2}u_2\right)$$
$$\text{i.e., } \dot{x}_7 = -\frac{Kr_2}{R_2Tg_2}x_5 - \frac{1}{Tr_2}x_7 + \left(\frac{1}{Tr_2} - \frac{Kr_2}{Tg_2}\right)x_8 + \frac{Kr_2}{Tg_2}u2$$

For Block 8:

$$x_8 + Tg_2\dot{x}_8 = -\frac{1}{R_2}x_5 + u_2$$
$$\text{i.e., } \dot{x}_8 = -\frac{1}{R_2Tg_2}x_5 - \frac{1}{Tg_2}x_8 + \frac{1}{Tg_2}u_2$$

For Block 9:

$$\dot{x}_9 = 2\pi T^0 x_1 - 2\pi T^0 x_5$$

For Block 10:

$$\dot{x}_{10} = B_1x_1 + x_9$$

For Block 11:

$$\dot{x}_{11} = B_2x_5 - x_9$$

The above state equations of the two-area system can be represented in matrix form as $\dot{x} = Ax + Bu$,

where A = (11x11)system matrix having constant coefficients

and B = (11x2) input or control matrix having constant coefficients

$$A = \begin{bmatrix} \frac{-1}{T_{P1}} & \frac{K_{P1}}{T_{P1}} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-K_{P1}}{T_{P1}} & 0 & 0 \\ 0 & \frac{-1}{Tt_1} & \frac{1}{Tt_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-Kr_1}{R_1 Tg_1} & 0 & \frac{-1}{Tr_1} & \left(\frac{1}{Tr_1} - \frac{Kr_1}{Tg_1}\right) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-1}{R_1 Tg_1} & 0 & 0 & \frac{-1}{Tg_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{T_{P2}} & \frac{K_{P2}}{T_{P2}} & 0 & 0 & \frac{K_{P2}}{T_{P2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{-1}{Tt_2} & \frac{1}{Tt_2} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-Kr_2}{R_2 Tg_2} & 0 & \frac{-1}{Tr_2} & \left(\frac{1}{Tr_2} - \frac{Kr_2}{Tg_2}\right) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{R_2 Tg_2} & 0 & 0 & \frac{-1}{Tg_2} & 0 & 0 & 0 \\ 2\pi T^0 & 0 & 0 & 0 & -2\pi T^0 & 0 & 0 & 0 & 0 & 0 & 0 \\ B_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & B_2 & 0 & 0 & 0 & -1 & 0 & 0 \end{bmatrix}; B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{K_{r1}}{Tg_1} & 0 \\ \frac{1}{Tg_1} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{Kr_2}{Tg_2} \\ 0 & \frac{1}{Tg_2} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

State Vector (x) $= \begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9 & x_{10} & x_{11} \end{bmatrix}^T$

Control Vector (u) $= \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$

5. DESIGN OF OPTIMAL CONTROLLER:

The control inputs are:

$$u_1 = k_{11}x_1 + k_{12}x_2 + \ldots\ldots\ldots + k_{1-10}x_{10} + k_{1-11}x_{11}$$

$$u_2 = k_{21}x_1 + k_{22}x_2 + \ldots\ldots\ldots + k_{2-10}x_{10} + k_{2-11}x_{11}$$

Where,

$$K = \begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} & k_{15} & k_{16} & k_{17} & k_{18} & k_{19} & k_{1-10} & k_{1-11} \\ k_{21} & k_{22} & k_{23} & k_{24} & k_{25} & k_{26} & k_{27} & k_{28} & k_{29} & k_{2-10} & k_{2-11} \end{bmatrix}$$

Hence the control law, $u = -kx$, where, k is the optimal gain matrix.

6. DETERMINATION OF OPTIMAL GAIN MATRIX (K):

The performance index (PI) of the system is given by:

$$PI = \frac{1}{2}\int_0^\infty \left(x^T Q x + u^T R u\right) dt$$

$$PI = \frac{1}{2}\int_0^\infty \left[(B_1 x_1 + x_9)^2 + (B_2 x_5 - x_9)^2 + (x_{10})^2 + (x_{11})^2 + (u_1)^2 + (u_2)^2\right] dt$$

$$PI = \frac{1}{2}\int_0^\infty \left[B_1^{\ 2} x_1^{\ 2} + 2B_1 x_1 x_9 + 2x_9^2 + B_2^{\ 2} x_5^2 - 2B_2 x_5 x_9 + x_{10}^2 + x_{11}^2 + u_1^{\ 2} + u_2^{\ 2}\right] dt$$

This results in the symmetric matrix Q $_{11x11}$ and R_{2x2} as follows:

$$Q = \begin{bmatrix} B_1^{\ 2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & B_1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & B_2^{\ 2} & 0 & 0 & 0 & -B_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ B_1 & 0 & 0 & 0 & -B_2 & 0 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

The matrices A, B, Q and R are known.
The optimal control is given by, u=- kx
The optimal gain matrix is: $k = R^{-1}B^{T}P$
where, ‘P’ is a real, symmetric and positive definite matrix which is the unique solution of matrix Riccati Equation:

$$A^{T}P + PA + Q - PBR^{-1}B^{T}P = 0$$

The closed loop system equation is:

$$\dot{x} = Ax + B(-kx) = (A - BK)x = A_c x$$

The matrix $A_c = (A - BK)$ is the closed loop system matrix. The stability of closed loop system can be tested by finding eigenvalues of A_c

7. CONCLUSION:

Automatic generation control is the primary control mechanism in modern interconnected power system. In this paper, a model of interconnected reheat type thermal power system comprising of two areas of different characteristics has been developed incorporating state-space concept and extended the study to illustrate optimal control strategies for automatic generation control. The optimal controller has been designed in state variable form and the control equations in continuous time have been obtained for the power system model under consideration.

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