A Comparative Analysis and Simulation of ALFC in Single Area Power System for Different Turbines

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Abstract— **The primary role of an automatic load frequency control (ALFC) is to controls the real power and frequency. State equations of system for a steam turbine (with and without reheating) and hydro turbines (with and without compensation) are proposed in this paper. Then by examining some factors such as turbine time constant, inertia constant, damping factor and governor speed regulation, the frequency control methods and influence of a small load variation are discussed.**

Keywords--load frequency control; steam and hydro turbines; transfer function; space analysis.

I. INTRODUCTION

In power system, real and reactive powers are independent of each other and controlled separately. The automatic voltage regulate (AVR) loop regulates the reactive power and voltage magnitude and the load frequency control (LFC) loop controls the real power and frequency. The operation objectives of the LFC are to maintain reasonably uniform frequency, to divide the load between generators, and to control the tie line interchange schedules [1, 2]. Therefore LFC is a very much important issue in power system operation and control for supplying sufficient and reliable electric power with good quality. Mechanical input power electrical generator is provided by different actuators including diesel engine, steam turbine, hydraulic and gas turbines. The frequency as a common factor in the whole power system depends on the active power balance. If such active power balance has not been achieved the frequency varies. Therefore, a load frequency control in power systems is essential. The aims of the LFC are firstly to minimize the errors of frequency and transmitted powers between regions and secondly, to diminish the steady state frequency error.

Control principles for the LFC system have been described in a few publications. A proportional-integral-derivative (PID) controller for power system LFC with systematic tuning method is presented in [3]. A new LFC scheme with a modified PID controller which guarantees the stability of the LFC loop for the wide control ranges of PID feedback gains has been proposed in [4]. In [5], dynamic performance of a combined cycle power station for frequency drop has been introduced. This combined power station consists of a steam turbine and a gas turbine that has efficiency larger than 50%. The gas turbine supplies two-third and steam turbine supplies one-third of the required power. In [6], the state equations of LFC system for a steam turbine with different parameters are proposed. Hydro-turbine has a large fixed cost but negligible variable cost. It can be quickly connected to the bus-bar and it can respond to the system frequency variations. It is also quickly loaded or unloaded. Control of a hydro turbine is easier and cheaper than that of steam turbines.

A PID tuning method based on the two-degree-of-freedom internal model control for load frequency control of power systems with non-reheat, reheat, and hydro turbines is discussed in [7]. A designing method based on quasi pole placement of a load frequency control combining a PID controller and a disturbance observer to deal with large scale wind power generations introduced in power systems proposed in [8].

In this paper we study the dynamic behavior and transient stability of ALFC system for steam and hydro turbines in the single area power system with parameters variation. This paper is organized as follows. In section II, the system equation in state space model and transfer function of the system is given. The effects of some main parameters and the analyses of eigenvalue have been reported in section III. Finally, the application of reheat in steam turbines and compensation in hydro turbine are discussed in section IV.

II. MATHEMATICAL MODEL

Mathematical modeling of the system is required for designing control systems. Analytical model is important tools for the prediction of dynamic performance and stability limits with different control law and system parameters. The simulation plays an important role in the design and analysis of the system and their controllers. State equations are commonly used in the simulation is procedure. The first step in the analysis and design of LFC systems is mathematical modeling of the system. The proportional–integral (PI) controller is common in process control or regulating systems. An advantage of the PI controller reduces the steady state error to zero by feeding the errors in the past forward to the plant.

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The block diagram of an ALFC system which has two loops is shown in Fig. 1, where P_D, P_C, P_E, P_G, P_V, P_M and Ω denote the load, reference set power, power error signal, governor output, steam value position or change in water gate, mechanical power output and frequency respectively and Δ denotes an incremental change. In Fig.1, $G_T(s)$ is the transfer function of turbine and $G_{CH}(s)$ is the transfer function of compensation [$G_C(s)$] or re-heater [$G_H(s)$] and given by:

$$G_{CH}(s) = \frac{\Delta P_V(s)}{\Delta P_E(s)} = \frac{1+T_Z s}{1+T_P s} \tag{1}$$

where $z=-1/T_z$ and $p=-1/T_p$ are the zero and pole of the transfer function, respectively. The $G_T(s)$, T_P and T_Z are with due attention to kind of turbine obtained. The integral controller adds a pole at origin and increases the system type by one and reduces the steady state frequency deviation to zero due to a step change of the load. The list of system main parameters and nominal value are shown in Table I. In the LFC without three mode controller, the output frequency is:

$$\Delta\Omega(s) = H_C(s)\Delta P_C(s) - H_D(s)\Delta P_D(s) \tag{2}$$

Equ.2 shows that the output frequency depends on both the load and reference set power where:

$$H_C(s) = \left.\frac{\Delta\Omega(s)}{\Delta P_C(s)}\right|_{\Delta P_D(s)=0} \tag{3}$$

$$H_D(s) = \left.\frac{\Delta\Omega(s)}{\Delta P_D(s)}\right|_{\Delta P_C(s)=0} \tag{4}$$

When an integral controller is used for the system, the closed loop transfer change function from the frequency to the load change for steam and hydro turbine are given by Equ.5 and 6.

$$G_{ST}(s) = \frac{\Delta\Omega(s)}{\Delta P_L(s)} = \frac{P_{ST}(s)}{Q_{ST}(s)} \tag{5}$$

$$G_{HT}(s) = \frac{\Delta\Omega(s)}{\Delta P_L(s)} = \frac{P_{HT}(s)}{Q_{HT}(s)} \tag{6}$$

TABLE I. SYSTEM PARAMETERS

Parameter	value
T_W	1
K_G	1
T_G	0.2
K_T	1
T_T	0.5
R	2
F_H	0.5
T_H	9
K_E	100
T_E	20
K_I	0.09
H	5

The transfer function is independent of the system input and considering a linear characteristic for the system, it shows a relationship between the input and the output. Transient response of the systems depends on the location of the transfer function poles on the s plane. Typically the characteristic equations of control system are of high orders and the transfer function poles are classified into dominant poles which are effective on dynamic behavior of the system and unimportant poles. A turbine is a complex dynamic system. Different types of turbines vary widely in characteristics. In this section state equations of LFC systems of steam turbine with reheat and hydro turbines with compensation is discussed and simulation results have been reported. For this analysis, the differential equations are expressed in the following matrix form:

$$\dot{X} = \frac{d}{dt}X = A\,X + B\,U \tag{7}$$

$$Y = C\,X \tag{8}$$

where A is the system matrix, B is the control matrix, X is the state variables vector, U is the input vector, C is the output matrix and D is the fed forward matrix. By choosing:

$$Y = [\Delta\Omega \quad \Delta P_M]^T \tag{9}$$

$$X = [\Delta\Omega \quad \Delta P_M \quad \Delta P_V \quad \Delta P_E \quad \Delta P_C]^T \tag{10}$$

The matrices B and C derived as follows and matrices A with due attention to kind of turbine obtained.

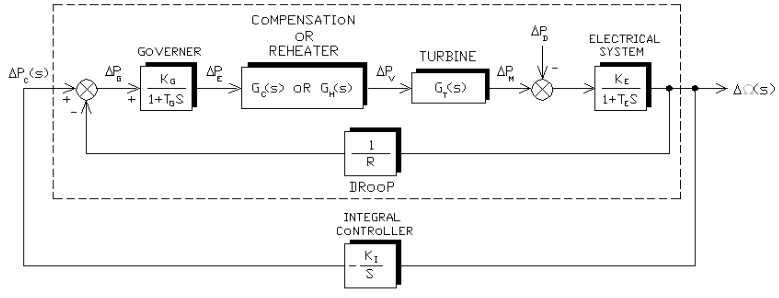

Figure 1. Block diagram of the LFC system with integral controller

$$B = \begin{bmatrix} -\frac{K_E}{T_E} & 0 & 0 & 0 & 0 \end{bmatrix}^T \tag{11}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix} \tag{12}$$

A. *Steam Turbine*

In general, there are two types of steam turbines, non-reheat and reheat. Reheat type steam turbines provide improved plant efficiency and always preferred in large plants. In simplest form, the turbine can be assumed to be a first order dynamic system expressed with the following transfer function:

$$G_T(s) = \frac{\Delta P_M(s)}{\Delta P_V(s)} = \frac{K_T}{1 + T_T s} \tag{13}$$

The turbine equipped with reheat consists of two levels of low- and high-pressure. Their rated power in pu is F_H and $1\text{-}F_H$ respectively. Turbine transfer function with reheat assuming a linear characteristic of the control valve and regardless of additional time constant associated with cross piping against the reheat time constant T_H can be considered as:

$$G_H(s) = \frac{\Delta P_V(s)}{\Delta P_E(s)} = \frac{1 + T_Z s}{1 + T_P s} = \frac{1 + T_H F_H s}{1 + T_H s} \tag{14}$$

For LFC system in steam turbine equipped a heater, matrix A is as follows as:

$$A = \begin{bmatrix} -\frac{1}{T_E} & \frac{K_E}{T_E} & 0 & 0 & 0 \\ 0 & -\frac{1}{T_T} & -\frac{K_T}{T_T} & 0 & 0 \\ -\frac{K_G F_H}{R\,T_G} & 0 & -\frac{1}{T_H} & \frac{1}{T_H} - \frac{F_H}{T_G} & \frac{F_H K_G}{T_G} \\ -\frac{K_G}{R\,T_G} & 0 & 0 & -\frac{1}{T_G} & \frac{K_G}{T_G} \\ -K_I & 0 & 0 & 0 & 0 \end{bmatrix} \tag{15}$$

The characteristic equation without integral controller is:

$$\begin{aligned} \Delta_S(s) = {} & s^4 + \left(\frac{1}{T_R} + \frac{1}{T_G} + \frac{1}{T_T} + \frac{1}{T_E}\right)s^3 + \\ & + \left(\frac{T_R(T_G + T_T + T_E) + T_E(T_G + T_T) + T_G T_T}{T_R T_G T_T T_E}\right)s^2 \\ & + \left(\frac{T_G + T_R + T_T + T_E}{T_R T_G T_T T_E} + \frac{F_H K_E K_G K_T}{R T_G T_T T_E}\right)s \\ & + \frac{1}{T_R T_G T_T T_E}\left(1 + \frac{K_E K_G K_T}{R}\right) \end{aligned} \tag{16}$$

B. *Hydro Turbine*

Power change and structure of hydro turbine depend on the height of water fall. The turbine converts the potential energy of the water into rotational kinetic energy of the turbine. If the hydro system operates with small load perturbations and the hydraulic coupling is ignored, in the simplest form, the transfer function of an ideal turbine is as follows:

$$G_T(s) = \frac{\Delta P_M(s)}{\Delta P_V(s)} = \frac{1 - T_W s}{1 + 0.5 T_W s} \tag{17}$$

The mechanical power is controlled by opening or closing valves regulation water flow. When more water passes through the turbine mechanical output on the shaft of the turbine increases. The transfer function of transient droop compensation can be written as:

$$G_C(s) = \frac{\Delta P_V(s)}{\Delta P_E(s)} = \frac{1 + T_Z s}{1 + T_P s} = \frac{1 + T_R s}{1 + \alpha T_R s} \tag{18}$$

where α is slopes ratio and T_R is resetting time and both of them is dependent on the T_W.

For LFC system in hydro turbine equipped with transient droop compensation, matrix A is as follows as:

$$A = \begin{bmatrix} -\frac{1}{T_E} & \frac{K_E}{T_E} & 0 & 0 & 0 \\ \frac{2K_G}{RT_G\alpha} & -\frac{2}{T_W} & \frac{2}{T_W} + \frac{2}{\alpha T_R} & -\frac{2}{\alpha}\left(\frac{1}{T_R} - \frac{1}{T_G}\right) & -\frac{2K_G}{T_G\alpha} \\ -\frac{K_G}{RT_G\alpha} & 0 & -\frac{1}{\alpha T_R} & \frac{1}{\alpha}\left(\frac{1}{T_R} - \frac{1}{T_G}\right) & \frac{K_G}{T_G\alpha} \\ -\frac{K_G}{RT_G} & 0 & 0 & -\frac{1}{T_G} & \frac{K_G}{T_G} \\ -K & 0 & 0 & 0 & 0_I \end{bmatrix} \tag{19}$$

The characteristic equation without integral controller is:

$$\begin{aligned} \Delta_H(s) = {} & s^4 + \left(\frac{1}{\alpha T_R} + \frac{2}{T_W} + \frac{1}{T_G} + \frac{1}{T_E}\right)s^3 + \\ & + \left[\frac{T_W + 2\alpha T_R + 2T_G}{\alpha T_G T_W T_R} + \frac{2}{T_E}\left(\frac{1}{T_G} + \frac{1}{T_W}\right)\right. \\ & \left. + \frac{1}{\alpha T_R\, T_E} - \frac{K_G T_R T_W}{R}\right]s^2 \\ & + \left[\left(\frac{2}{\alpha T_G T_W T_R} + \frac{2}{\alpha T_E T_W T_R} + \frac{1}{\alpha T_G T_E T_R}\right.\right. \\ & \left.\left. + \frac{2}{T_E T_G T_W} + \frac{2K_G K_E}{R\alpha T_E T_G}\left(\frac{1}{T_W} - \frac{1}{T_R}\right)\right)\right]s + \frac{1}{K_E} + \frac{K_G}{R} \end{aligned} \tag{20}$$

III. EIGENVALUE ANALYSIS AND COMPARISON BETWEEN DIFFERENT TURBINES

For reliable service, a power system must remain stable and capable of withstanding a wide range of disturbances. Here the effects of system physical parameters on the frequency response to the load variation are examined. The eigenvalue of the system matrix (A) can be used to determine the dynamic characteristics of the studied system subject to small perturbed conditions around the specified operating point. The dynamic response of frequency deviation for a step change in the load and different states are compared in Fig. 2 and 3 with and without integral controller respectively.

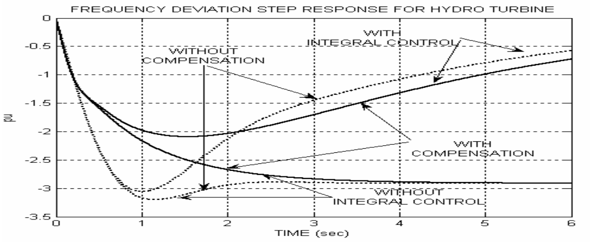

Figure 2. Comparison of the dynamic response of frequency deviation with and without integral control for a step change in the load for hydro turbine with and without compensation

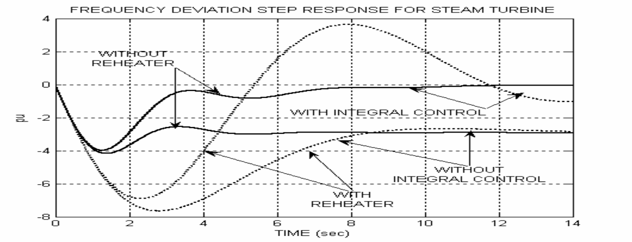

Figure 3. Comparison of the dynamic response of frequency deviation for a step change in the load with and without integral control for steam turbine with and without re-heater

A. Change of theturbine parameters

Influence of changing of T_T and T_W on the frequency response is simulated in this section.

Turbine time constant (T_T): The turbine time constant has no role in final frequency response but it affects the overall response and its damping. Fig. 4 show the effects of T_T variation on frequency response in the two turbines with and without controller. The characteristic equation roots of different values for steam turbine of T_T with and without integral control are shown in Table II and III.

Water statring time (T_W): The water starting time for rated conditions is calculated from the plant drawings and measured flows between the surge tank and turbine inlet. For hydro-generator without compensator, increase of T_w makes closer the complex poles to the imaginary axis and damping factor decreases. If there is no compensator, the value of T_W is more limited. This leads to an oscillatory response. However, in hydro-generator with compensator, the complex poles are not so close to the axis and in the same time one of real poles is close to the axis. Figs. 5 and 6 show the response frequency and mechanical power of system affected by varying T_W respectively, with and without compensation.

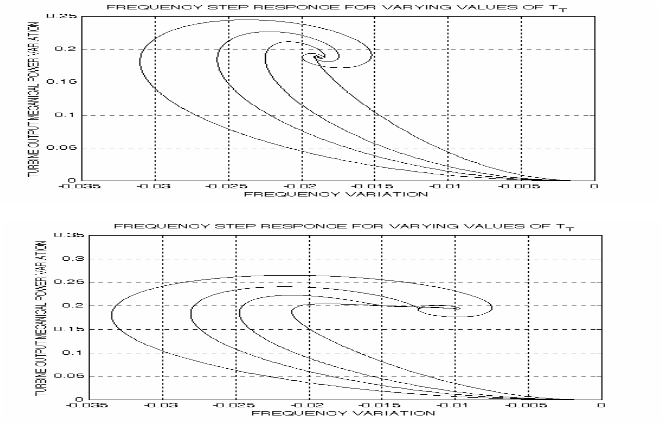

Figure 4. Frequency variations in terms of turbine output mechanical power for T_T variation (a) without reheat (b) equipped with reheat

TABLE II. CHARCTERISTIC EQUATION ROOTS FOR A TURBINE WITHOUT REHEATER OF DIFFERENT VALUES OF T_T

T_T	With Controller	Without Controller
0.5	–5.745 –0.308 –0.499 ± j1.515	–5.772 –0.639 ± j1.602
1.5	–5.224 –0.293 –0.101 ± j0.986	–5.235 –0.241 ± j1.017

TABLE III. CHARCTERISTIC EQUATION ROOTS FOR A TURBINE WITHOUT REHEATER OF DIFFERENT VALUES OF T_T

T_T	With Controller	Without Controller
0.5	–5.265 –1.332 –0.222 –0.171 ± j0.541	–5.277 –1.099 –0.393 ± j0.418
1.5	–5.068 –0.525 –0.228 –0.004 ± j0.524	–5.071 –0.451 –0.153 ± j0.505

B. Change of the reheat parameters

The turbine with heater has time constant of the heater and high-pressure level. Influence of changing these two parameters on the frequency response is simulated in this section.

High pressure factor (F_H): The output power of a high pressure turbine is shown by F_H and the low pressure one is represented by 1-F_H. Therefore, the more the F_H, the higher power is generated by a high pressure turbine and less steam is enters into the reheat system. Amplitude of high-pressure factor affects on the damping the system but not the final frequency response. Fig. 7 show the effect of this factor variation. The characteristic equation roots of different values for steam turbine of F_H with integral control are shown in Table IV. Larger F_H factor leads to a smaller proportion of the reheated steam. Quick change of the load causes transient frequency drop of the frequency response. A larger F_H is better for transient response of the system. In this case smaller proportion of the steam is reheated.

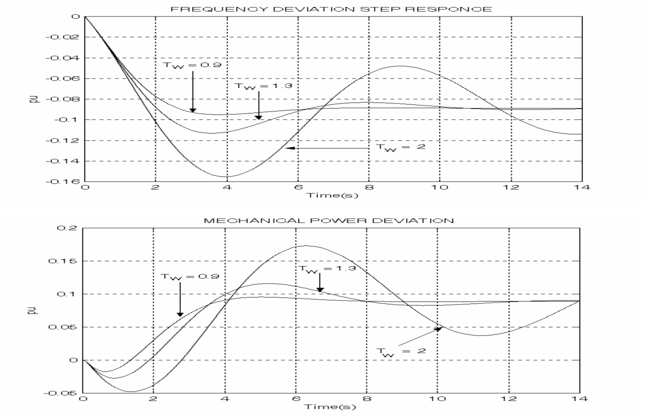

Figure 5. Response frequency and mechanical power affected by variation in T_W without compensation

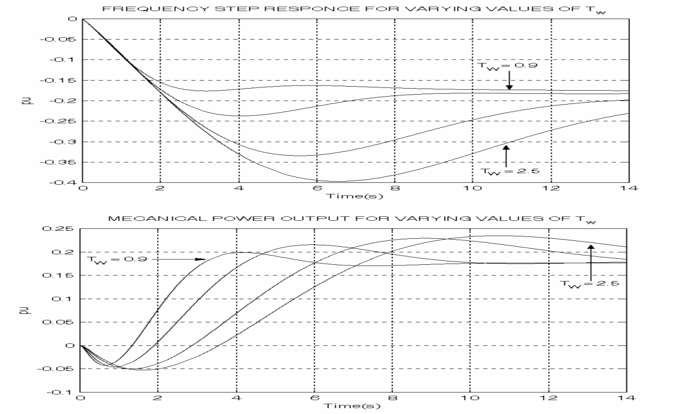

Figure 6. Response frequency and mechanical power affected by variation in T_W with compensation

But the thermal efficiency of the power station reduces and the effective life time of the turbine reduces. Therefore small high-pressure factor must be selected.

Reheat time constant (T_H): The largest time constant in the control of steam flow is due to re-heater. Fig. 8 show the system frequency response curves by varying the reheat time constant. The characteristic equation roots for a turbine with reheater of different values of T_H with integral control are shown in Table V. Changing reheater time constant influence the damping and overshoot of the system response but it has no effect on the final frequency response.

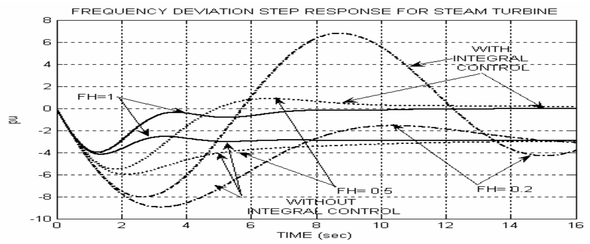

Figure 7. Time variations of frequency for different high pressure factor in turbine with reheat

TABLE IV. EGINVALUES FOR A TURBINE WITHOUT REHEATER OF DIFFERENT VALUES OF F_H WITH INTEGRAL CONTROL

F_H=0.2	F_H=0.5	F_H=1
−5.177	−5.422	−5.745
−1.631	−0.563	−0.308
−0.231	−0.192	−0.111
$-0.061 \pm j0.503$	$-0.492 \pm j0.781$	$-0.499 \pm j1.515$

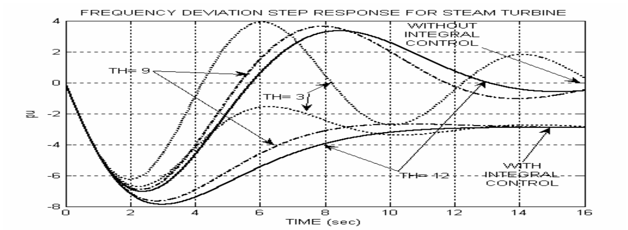

Figure 8. Time variations of frequency for different value of reheat time constant

TABLE V. EGINVALUES FOR A TURBINE WITHOUT REHEATER OF DIFFERENT VALUES OF T_H WITH INTEGRAL CONTROL

T_H=3	T_H=9	T_H=12
−5.238	−5.265	−5.268
−1.674	−1.332	−1.278
−0.277	−0.222	−0.198
$-0.097 \pm j0.780$	$-0.171 \pm j0.541$	$-0.195 \pm j0.494$

IV. CONCLUSION

A simple method using state equations has been presented to analyze the frequency response of the LFC system. Then the effects of parameter variation of two turbines on the system behavior with and without reheat for steam turbine and with and without compensation for hydro turbine have been shown. In controlling the steam flow and turbine output power, the largest time constant is associated with the reheat and the response of turbines equipped with reheat is slower than the ones without the reheat. Input water of a hydro-generator for generating the required active power can be regulated by the shutter. As frequency deviates of frequency from the rated value, system regulates the input water of the turbine and controls the generated electric power.

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