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Small Signal Study Generating Units Dynamic Behavior with Reheat Steam Turbine and Transient Droop Hydraulic Turbine

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Abstract

The load of consumer demand is constantly changing. Therefore, controlling the generating units is the first issue for designing the power systems. In this paper, the steam generation unit and hydraulic generation unit are studied and simulated. The steam turbine has a re-heater and the hydraulic turbine has a transient droop compensation. The linearized math-ematical models of the first-order system of two generating units are expressed in the state space. The transient dynamic behavior of two generating units is investigated and com-pared with small changes in load demand. Also, the transfer function of the ratio of fre-quency deviation which changes with the changes in the load demand is shown for each unit. MATLAB software is used for simulation.

Keywords: Generating Units, Steam Turbine, Hydro Turbine, State Space.

1. INTRODUCTION

Turbines are very important devices in the industry because almost all electricity is produced by converting mechanical energy through a turbine into electrical energy through a generator [1,2]. According to their type of applications and forms, turbines are used in wind power plants [3,4], hydroelectric power plants [5,6], gas plants [7,8], and propulsion power [9,10].

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Hydropower plants and steam power plants are the main power plants to produce energy in the power system [11,12]. Load consumption changes at different hours. Many generating units are responsible for supplying energy to the grid, and changes in consumption load must be divided between the units [13,14]. By controlling the input mechanical power of the generator, its active power can be controlled [15]. Therefore, by opening or closing the steam valve or the water gate, the flow of steam or water on the turbine is adjusted and the mechanical power is controlled [16,17].

The passage of active power and reactive power in a transmission network is different from each other and they are subjected to different control methods. Active power control depends on frequency control and reactive power control depends on voltage control [18,19].

Frequency is a common factor throughout the system, and the effect of changing the active power at one point is reflected in the frequency throughout the system [20,21].

In this paper, a generation unit with a reheat steam turbine and a generation unit with a transient droop hydraulic turbine are studied and simulated. The effect of small changes in load demand on the dynamic transient behavior of two generating units has been investigated and compared. By drawing the bode diagram of the defined transfer function for each generating unit, gain and phase are also determined. The simulation results have been obtained using MATLAB software. The structure of the paper is as follows: In section 2, the equations of production units are expressed in the state space. In section 3, based on the definition of the transfer function, two transfer functions are considered for each production unit. In section 4, the simulation results of the dynamic behavior of production units to small load changes are presented. Finally, the conclusion is stated in section 5.

2. GENERATING UNITS SYSTEM EQUATIONS IN STATE SPACE

In this section, the equations of the generating unit with hydraulic turbine and the generating unit with reheat steam turbine are expressed in the state space. In any system, the main output is frequency deviation changes.

For each system, two inputs are considered, which are changes in load demand or load disturbance ($u_1=\Delta P_D$) and changes in the input command signal ($u_2=\Delta P_C$). The input command signal in the load frequency control closed loop system is determined by the frequency deviation signal through the controller. Each generating unit without a controller has four state variables. Variations of output frequency deviation are considered as x_1. The mechanical power output of the turbine is shown by x_2, the output of the reheater or the transient droop compensation of the hydraulic turbine is shown by x_3, and the output of the governor is shown by x_4.

2.1. Hydraulic Turbine

Among the hydraulic turbine performance parameters, we can mention flow, head, and rotational speed [22,23]. The time constants of the hydraulic turbine are smaller than the time constants of the tank, penstock, and surge chamber, therefore, the hydraulic turbine can be considered as a memoryless element [24,25].

Fig. 1 shows the block diagram of the generating unit with a hydraulic turbine. The first-order differential equations of the system in the state space are:

$$\frac{d}{dt}x_1 = -\frac{1}{T_P}x_1 + \frac{K_P}{T_P}x_2 - \frac{K_P}{T_P}u_1 \tag{1}$$

$$\frac{d}{dt}x_2 = \frac{-2}{T_W}x_2 + \frac{2}{T_W}x_3 - 2\frac{d}{dt}x_3$$
$$= \frac{2K_G}{\alpha R_P T_G}x_1 - \frac{2}{T_W}x_2 + \left(\frac{2}{T_W} + \frac{2}{\alpha T_R}\right)x_3$$
$$-\left(\frac{2}{\alpha T_R} - \frac{2}{\alpha T_G}\right)x_4 - \frac{2K_G}{\alpha T_G}u_2 \tag{2}$$

$$\frac{d}{dt}x_3 = -\frac{1}{\alpha T_R}x_3 + \frac{1}{\alpha T_R}x_4 + \frac{1}{\alpha}\frac{dx_4}{dt}$$
$$= -\frac{K_G}{\alpha R_P T_G}x_1 - \frac{1}{\alpha T_R}x_3 + \left(\frac{1}{\alpha T_R} - \frac{1}{\alpha T_G}\right)x_4 \tag{3}$$
$$+\frac{K_G}{\alpha T_G}u_2$$

$$\frac{d}{dt}x_4 = -\frac{K_G}{R_P T_G}x_1 - \frac{1}{T_G}x_4 + \frac{K_G}{\alpha T_G}u_2 \tag{4}$$

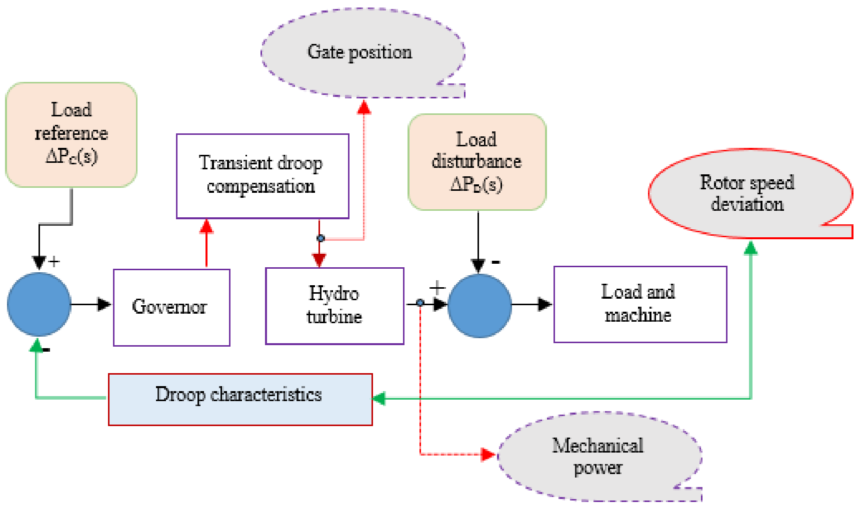

Fig. 1. Generating unit block diagram with hydraulic turbine.

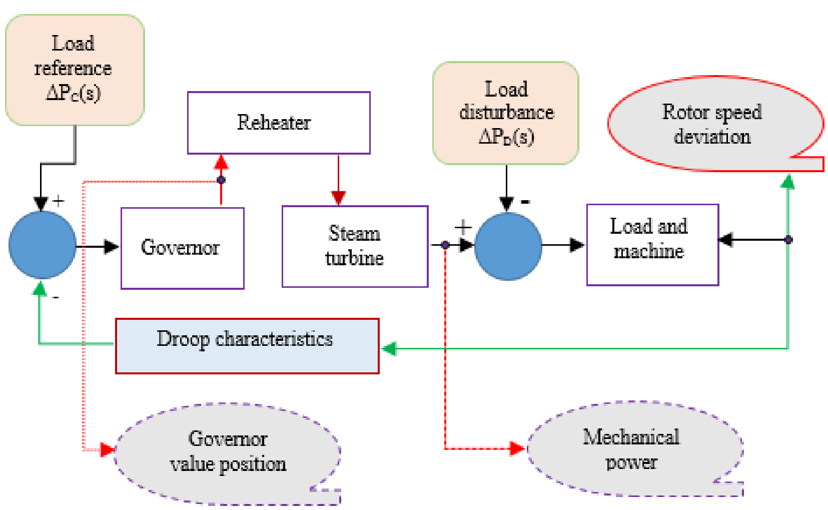

Fig. 2. Generating unit block diagram with reheat steam turbine.

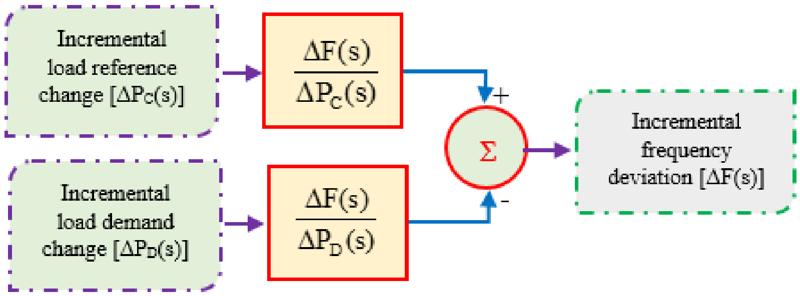

Fig. 3. Generating unit block diagram with reheat steam turbine.

Table 1. ***Hydraulic turbine parameters.***

Parameter	Symbol	Nominal value
Water starting time	T_W	1.5 sec
Reset time	T_R	7.13
Governor time constant	T_G	0.3
Governor steady state gain	K_G	1
Steady-state gain of the electrical system	K_P	1
Time constant of the electrical system	T_P	15
Permanent droop	R_P	0.05
Temporary droop	R_T	0.22

Table 1 contains the parameters of the hydraulic turbine along with the nominal values.

For stable operation in the islanding condition, the amount of temporary droop (R_T) and reset time (T_R) is determined according to the water start time (T_W) and mechanical start time [26,27]. Also, α is equal to the ratio of R_T to R_P.

2.2. Reheat Steam Turbine

Steam turbines are classified into different categories based on purpose and working pressure, which include: condensing steam turbine, back-pressure steam turbine, reheat steam turbine, and turbine with steam extraction.

In a reheat cycle, expansion takes place in two turbines. The steam is expanded in the high-pressure turbine, then returned to the boiler, and reheated at constant pressure [28,29].

Fig. 2 shows the block diagram of the generating unit with reheat steam turbine. The first-order differential equations of the system in the state space are:

$$\frac{d}{dt}x_1 = -\frac{1}{T_P}x_1 + \frac{K_P}{T_P}x_2 - \frac{K_P}{T_P}u_1 \tag{5}$$

$$\frac{d}{dt}x_2 = -\frac{1}{T_T}x_2 + \frac{K_T}{T_T}x_3 \tag{6}$$

Table 2. ***Reheater steam turbine parameters.***

Parameter	Symbol	Nominal value
High pressure coefficient	F_H	0.3
Reheater time constant	T_R	7 sec
Governor time constant	T_G	0.3
Governor steady state gain	K_G	1
Steady-state gain of the electrical system	K_P	20
Time constant of The electrical system	T_P	20
Permanent droop	R_P	0.05
Turbine time constant	T_T	0.3
Turbine gain	K_T	1

$$\frac{d}{dt}x_3 = -\frac{K_G F_H}{T_G R_P}x_1 - \frac{1}{T_R}x_3 + \left(\frac{1}{T_R} - \frac{F_H}{T_G}\right)x_4 + \frac{K_G F_H}{T_G}u_2 \tag{7}$$

$$\frac{d}{dt}x_4 = -\frac{K_G}{T_G R_P}x_1 - \frac{1}{T_G}x_4 + \frac{K_G}{T_G}u_2 \tag{8}$$

The response of a steam turbine with reheater is much slower than a steam turbine without reheater, because in controlling steam flow and turbine power, the largest time constant belongs to the reheater [30,31]. Table 2 contains the parameters of the reheat steam turbine along with the nominal values.

3. GENERATING UNIT MODEL TRANSFER FUNCTION

In the process of designing control systems, it is important and necessary to display suitable mathematical models for the system. One of the methods of displaying dynamic systems is the transfer function of the system model. In each generation unit, the aim is to investigate the frequency deviation changes. Therefore, due to the existence of two inputs in each unit, two transfer functions can be defined in relation to the output: the transfer function of frequency deviation changes to load changes and the transfer function of frequency deviation changes to command signal changes. Fig. 3 shows how the transfer functions relate to the output in open loop system.

Both generating units without controller are fourth-order systems. The frequency deviation changes in an uncontrolled area which can be expressed based on transfer functions as follows:

$$\Delta F(s) = H_{FC}\Delta P_C(s) - H_{FD}\Delta P_D(s) \tag{9}$$

where the functions $H_{FC}(s)$ and $H_{FD}(s)$ are the ratios of frequency deviation to input load changes and set point changes, respectively.

Table 3. ***Eigenvalues in generating units for normal conditions.***

Generating unit	Eigenvalues	damping coefficient
Steam	-2.1918	1
	-4.1926	1
	-0.2376±j0.3535	0.5578
Hydraulic	-0.1734	1
	-4.1483	1
	-0.2216±j0.4729	0.4243

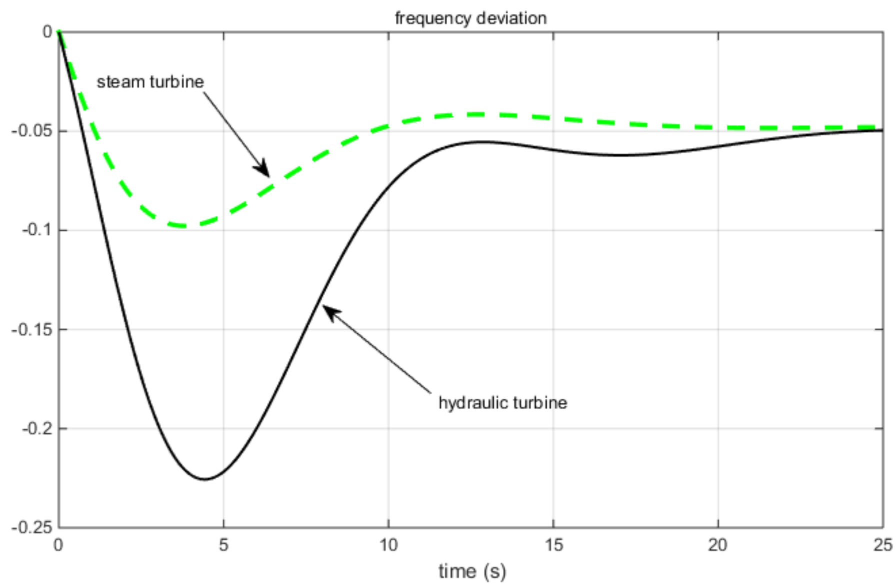

Fig. 4. Frequency deviation changes for step changes in load demand.

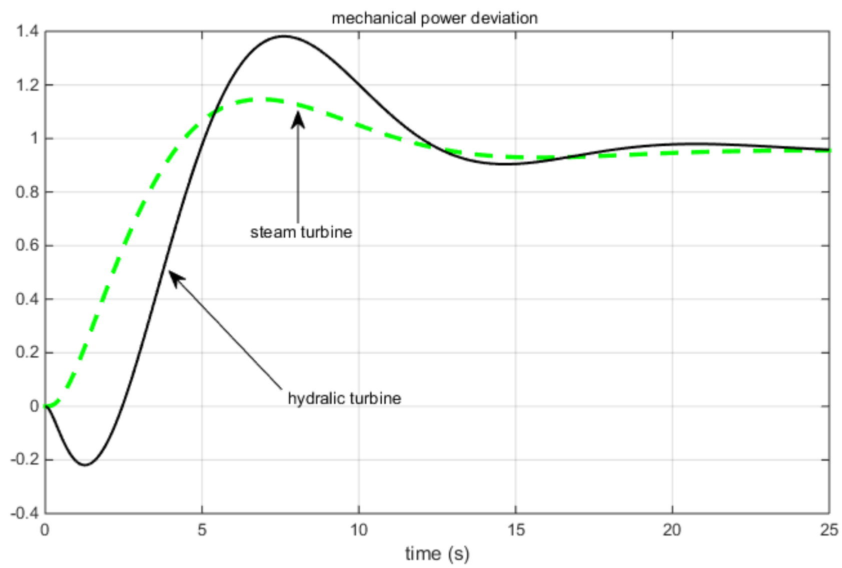

Fig. 5. Mechanical power changes for step changes in load demand.

Table 4. ***Open-loop frequency response characteristics of generating units.***

Generating unit	Gain margin	Phase margin	Crossover frequency
Steam	25.2589 dB	-5.82^{O}	0.4198 rad/s
Hydraulic	5.3413 dB	-139.42^{o}	0.3429 rad/s

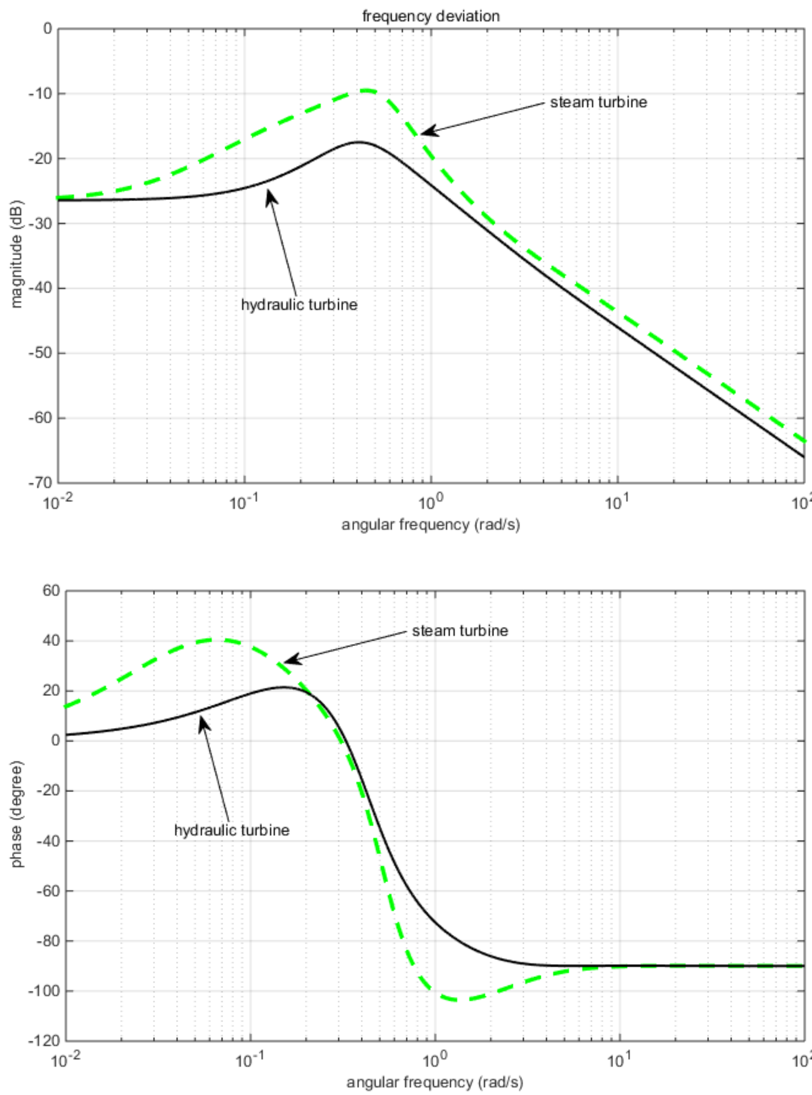

Fig. 6. Comparison of close-loop frequency response characteristics of production units.

4. SIMULATION RESULTS

In this section, the results of the simulation using system equations in the state space for two generating units are displayed in three states: a) Simulation of the transient dynamic behavior of the generating units for the normal state, b) Investigating the effect of changes in reheater parameters in the steam generating unit and c) Investigating the impact of changes in the transient droop compensation parameters in the hydraulic generating unit.

In each part, the eigenvalues of the system matrix are determined and the damping coefficient of the oscillating modes is calculated.

4.1. Generating unit's dynamic behavior Comparison

Eigenvalues for two generating units are given in table 3. Also, the frequency response of two units for normal conditions is mentioned in table 4. The response of frequency changes and mechanical power changes for step changes in load demand are shown in Figs. 4 and 5**,** respectively.

The comparison of the frequency response of the transfer function for two production units is shown in fig. 6. The considered transfer function is the frequency deviation changes to load demand changes.

As can be seen from the simulation results and eigenvalues, there is a difference in the transient part of the step response of the production units, but their permanent response is the same.

4.2. Changing the reheater parameters of the generating steam unit

Table 5 shows the system modes for three different values of high-pressure coefficient. By increasing the value of F_H, the overshoot in the step response of the system increases and more time is needed for the system to reach a stable state. In this case, for the above three values, the steady state response of the frequency deviation is the same.

Table 5. ***Eigenvalues in steam generating unit for high-pressure coefficient changes.***

High pressure coefficient	Eigenvalues	damping coefficient
F_H=0.3	-2.1918	1
	-4.1926	1
	-0.2376±j0.3535	0.5578
F_H=0.5	-1.4579	1
	-4.4395	1
	-0.4811±j0.1614	0.9480
F_H=0.7	-0.2206	1
	-4.6279	1
	-1.0055±j0.7883	0.7570

Table 6. ***Eigenvalues in hydraulic generating unit for rest time constant changes.***

Reset time constant	Eigenvalues	damping coefficient
T_R=2.63	-0.4351	1
	-6.3853	1
	-0.4101±j1.2035	0.3225
T_R=7.13	-0.1734	1
	-4.1483	1
	-0.2216±j0.4729	0.4243
T_R=10.63	-0.1071	1
	-3.8043	1
	-0.1511±j0.3192	0.4289

Table 7. ***Open-loop frequency response characteristics of hydraulic generating units.***

Reset time constant	Gain margin	Phase margin	Crossover frequency
T_R=2.63	3.0138 dB	-86.37°	0.9099 rad/s
T_R=7.13	5.3413 dB	-139.42°	0.3429 rad/s
T_R=10.63	5.3014 dB	-152.92°	0.2200 rad/s

4.3. Changing the compensation parameters of the generating hydraulic unit

System modes are represented in table 6and the phase margin and gain margin for three different values of reset time constant are represented in table 7.

With the reset time decrease, the crossover frequency value increases, but the gain margin and phase margin will decrease, in other words, the control system becomes more oscillatory but faster.

5. CONCLUSION

In this paper, the small signal study of two generating units of steam and hydro was presented. The steam unit had a turbine equipped with a reheater and the hydro unit had a turbine equipped with a transient droop compensation. The dynamic behavior of two generating units has been compared in terms of eigenvalues, transient response to step changes in load demand, and frequency response of the transfer function of frequency deviation changes to load demand changes.

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