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Impact of Hydro-Turbine and Governor Parameters on Stability of Grid Connected Power System

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Abstract: Hydro-turbine and governor parameters affect power system stability. It is essential to identify the parameters of the hydraulic system, turbine, and governor to improve the power-system stability. In this study, we carry out the identification of parameters using popular linear analysis techniques using SIMPOW software. The grid-connected power system Tala Hydropower Station is considered for the study. We identify how the parameters of the hydraulic system, turbine, and governor affect the power-system stability. The governor parameters such as permanent droop, temporary droop, filter time constant and servo time constant affect the stability of the grid-connected system. The parameters of the hydraulic system are surge impedance, friction factor of penstock, penstock elastic time constant, partial derivative of flow with respect to head, partial derivative of mechanical torque with respect to head, partial derivative of mechanical torque with respect to gate opening and partial derivative of flow with respect to gate opening affect the grid connected system.

Keywords: Power System Stability, Hydro-Turbine Parameters, Governor parameters, damping ratios, SIMPOW, linear analysis

1. Introduction

Power System stability is defined as the ability of the power system to regain equilibrium after being subjected to a physical disturbance. Power systems are nonlinear and their stability depends on both the initial conditions and the size of the disturbance. Before a fault occurs, a power system is operating at a stable steady-state condition. The transient stability problem of power system is used to assess whether the system will reach an acceptable steady-state operating point following the fault [1].

Transient stability studies are from the stability point of view, in which the system responds to a large disturbance such as a short circuit or a line tripping. When such a fault occurs, large currents and torques are produced, and action must be taken quickly if system stability is to be maintained. Before the fault occurs, the power system is operating in a stable steady-state condition. The power system's transient stability problem is an assessment of whether the system will reach an acceptable steady-state operating point following the fault [1].

If a large load is suddenly connected or disconnected from the system, or if the protection equipment suddenly disconnects the generating unit, there will be a long-term distortion in the power balance between what the turbines deliver and what the loads consume. This imbalance is initially covered by the kinetic energy of the rotating rotors of the turbines, the generators and the motors; as a result, the frequency in the system will change. This is called which as frequency stability and control [1].

A number of studies have been carried out in the field of hydropower-plant stability. One study was carried out to study on the effects that hydro-turbines and governors have on power systems' low-frequency oscillations. The results showed that the parameters of hydro-turbines and governor speed influence the oscillation modes and proposed a further study of the hydraulic system, including the water system, hydro-turbine, and governor, to ensure a detailed analysis of

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the low-frequency oscillations in a hydropower plant's power system [2]. An assessment of the effect that hydroelectric power plants' governor settings have on low-frequency inter-area oscillations close to 0.15Hz was also carried out [3]. It proposed that removing sources of negative damping would significantly enhance the system's damping performance. A study on frequency stability in an isolated power system was conducted [4]. Frequency stability is a critical problem for isolated power grids. It studied the effect that the parameter settings had on the governor system, excitation control system, and the load characteristics; they proposed the use of stabilizers with excitation to improve power systems' dynamic stability.

A study on the mechanism by which governor control impacts power-system dynamics was carried out [5]. Based on the analysis of the frequency response, it obtained a new concept of boundary response. It found that the boundary frequency of a typical speed-control loop in a hydro-turbine governing system is between 0.1 and 0.3 Hz; for the typical electrical power-control loop in a hydro-turbine, the frequency is between 0.2 and 0.5Hz. It studied the possibilities of producing damping with the turbine governor, which was ignored in the past. Although this method is not used often, it can be explored for practical use in the future.

In this study, we will identify the parameters of hydro-turbine, governor and hydraulic system affecting the power system stability in SIMPOW as suggested in [2].

A. Power Station Model

We used the case of Tala Hydropower Station in Bhutan for the study. This station has a capacity of 1020 MW and consists of a diversion dam (with 9.8 Mm^3 pondage to provide peak capacity), three desilting chambers, a 6.8-m diameter head-race tunnel, a surge shaft of restricted orifice type and having diameter of 15m(top)/12m(bottom), two pressure shafts of 4.0 m diameter, six 2.3 m diameter penstocks, an underground power house with an installed capacity of 1020 MW (provided by 6 generating units, each of 170-MW capacity), and a 3.084-km tail-race tunnel. The units operate under a net head that ranges from 824.54 to 809.57 m; the rated head is 819 m. Two network configurations are considered for the study: a grid-connected network configuration system and an isolated power system [6].

The single-line diagram of Tala Hydropower Station, which is a grid-connected power system, is given in Figure.1. In Area 1, there are six generators (G1 through G6), each of 170 MW capacity, which are connected to Bus B1 through Bus B6, respectively. The power generated by each unit (13.8 kV) is stepped-up to 400kV through 13.8/400kV/$\sqrt{3}$ step-up transformers (TF1 through TF6). The high-voltage windings for all transformers are connected to common Bus B7.

A shunt reactor of 63MVA is connected to the common bus to consume reactive power, which keeps the voltage at the required level. The evacuation of power from 400 kV at Bus B7 is made using three 400-kV transmission lines, each having a length of 140 km, to Bus B13, which is the stiff grid in Area 2. The fourth line connects Bus B7 and Bus B8, and it has a length of 50 km. There is a three-winding transformer (TF7) with a rating of 200 MVA, 400/220/33kV at the substation in Area 2.The primary winding of the transformer is connected to Bus B8 at 400kV, and the secondary winding is connected to Bus B9, for which a load of 130 MW is connected. The third winding is connected to Bus B10. There is a 16-MVA generator (G7) connected to Bus B12 in Area 3. The power from generator G7 is stepped up from 6.6kV to 220kV through a 16-MVA transformer. There is a line of 100km connecting Bus B11 and Bus B10 and a line of 120 km connecting Bus B8 to Bus B13. Bus B13 is a stiff grid located in Area 4.

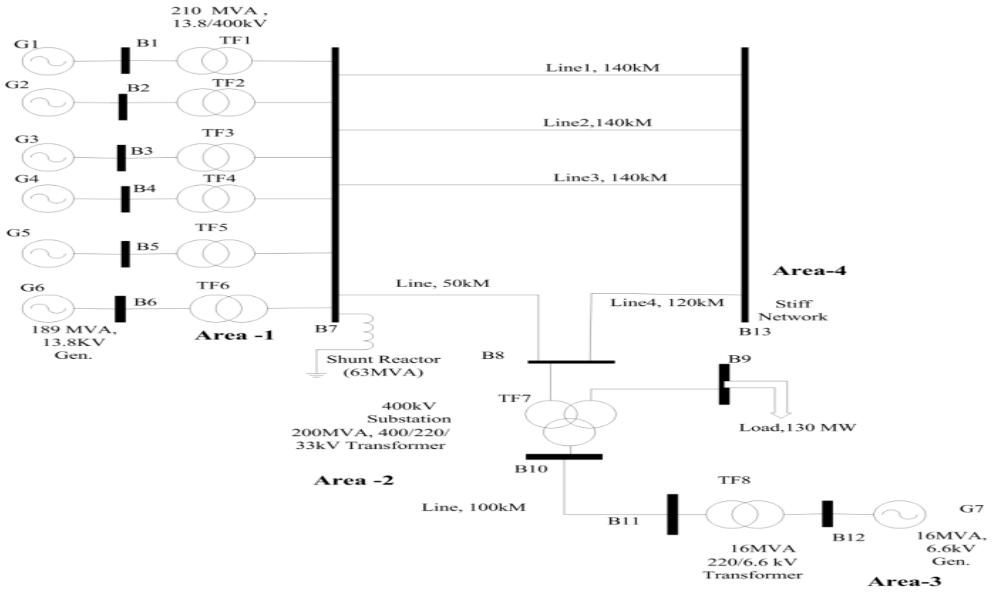

Figure 1. Single-line diagram of the grid-connected Tala Hydropower Station

2. Methodology

The software used in this project is SIMPOW [7], which is highly integrated for the simulation of power systems and which has wide range of applications. It focuses on linear analysis and dynamic simulation in the time domain as well as on analysis in the frequency domain. SIMPOW provides unique simulations and consists of analytic features that help in ensuring efficient planning, expansion, and utilization of electrical power systems. The approach used in the study is linear analysis. These techniques have been widely used to study the dynamic performance of power systems since the early 1970s [8]. These techniques have also been applied in many areas of power-system engineering, including modal analysis and control system design. They are used in practical applications, as they provide insights into the dynamic characteristics of a power system that cannot be provided from time-domain simulations alone. These features make linear analysis techniques valuable complements to time-domain simulation programs. There are many current applications of linear analysis techniques: coordination of power-system stabilizers and fact controllers; small-signal stability analysis based on time-domain identified models; and online applications for determining the online critical mode in the system with the worst damping.

A. Models

Models of hydraulic turbines, governors, generators, and excitation are required for carrying out the simulation work. Various models of hydraulic turbines are used for simulation.

A.1. DSLS/HYTUR/ turbine model

The second type of hydro-turbine used in T7 (for G7) is of type DSLS/HYTUR/ and is available in the SIMPOW Library [7]. The block diagram of the turbine is given in Figure 2.

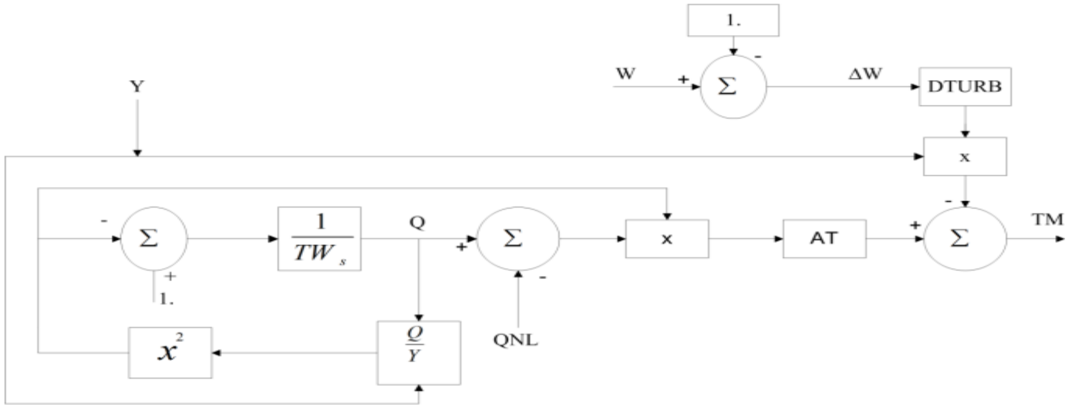

Figure 2. Block diagram of Hydro-turbine Type DSLS/HYTUR/

;Y = gate opening; TM= mechanical torque.
The parameters for the turbine are given in Table 1.

Table 1. *Parameters of Hydro-Turbine Type DSLS/HYTUR*

Description	Values
Rated mechanical power	14.7
Water time constant(s)	1.00
Turbine gain	1.1
Turbine damping	0.3
No-load flow	0.1

A.2 The Turbine parameter model

This model takes surge tank, elastic water column, and turbine parameters into account. It is not available in the SIMPOW library; we obtained it from a master's thesis carried out by Helle, 2011 [9]. We concluded that this model represented the dynamics of a hydraulic system with the highest accuracy. This model represents the hydraulic system of Tala Hydropower Station, which is why we considered it for the simulation. It includes a surge tank and an elastic water column, which is referred to as the water hammer effect. The two input parameters are gate position(Y) and the speed difference between nominal and actual speed, $\Delta\omega$; the output parameter is mechanical power. The flow in the head-race tunnel is passed to a summation point, which represents the flow conditions at the inlet to the surge tank. By making use of the flow conditions at the surge tank and the storage constant of the surge tank (C_s), we find the resulting head in the surge tank.

Surge tank natural period (T_s) is the period of the oscillations between the surge tank and the reservoir and is defined as

$$T_s = 2\pi\sqrt{\frac{A_s L_t}{A_t g}} \qquad (1)$$

;where A_s is the surge tank cross-sectional area (m2), L_t is thelength of the tunnel (m), A_t is the tunnel cross-sectional area (m^2), and g is the acceleration due to gravity (m/s^2). The block diagram is given in Figure 3.

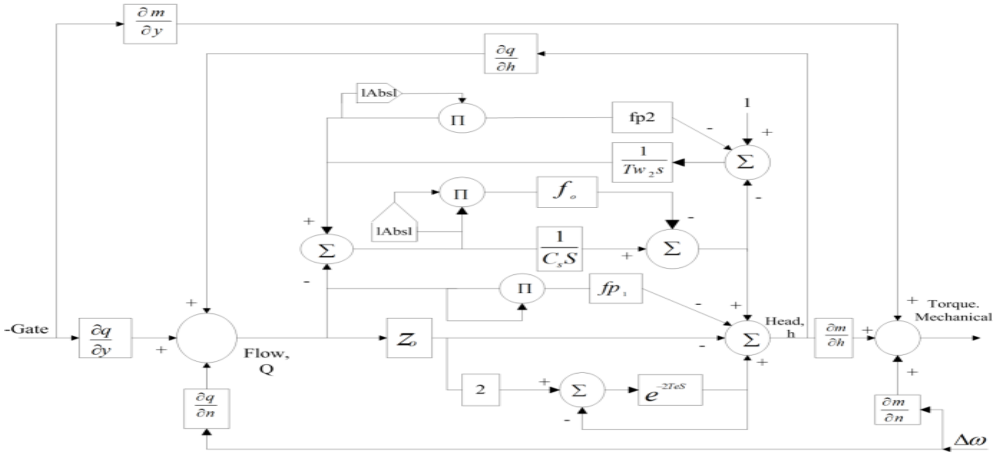

Figure 3. Block diagram of the turbine parameter model.

Water starting time (T_W) is defined as the time it takes to accelerate the water column from zero to the rated flow using the rated head (neglecting friction); it is defined as

$$T_w = \frac{L}{gA}\frac{Q_0}{h_0} \tag{2}$$

; where L is the length (m),A is the cross-sectional area of duct (m^2), g is the acceleration due to gravity (m^2/s), Q_0 is the rated volumetric flow (m^3/s), and h_0 is therated head (m). For a duct with varying cross-section, the sum of the *L*/*A* relationship should be used.

Penstock elastic time constant (T_e) is defined as the time it takes for a pressure wave to travel from the turbine to the nearest surface with atmospheric pressure, which is usually the surge shaft or reservoir:

$$T_e = \frac{L}{a} \tag{3}$$

;where L is the length to the nearest atmospheric pressure (m) and a is the pressure wave travel velocity (m/s).

Storage constant of surge tank ($\mathbf{C_s}$) is defined as

$$\boldsymbol{C_s} = \frac{\boldsymbol{A_s * h_{base}}}{\boldsymbol{q_{base}}} \tag{4}$$

; where $\boldsymbol{C_s}$ is given in seconds and A_s is the cross-sectional area of the surge chamber (m^2).
Surge impedance of the penstock constant (Z_o) is as given as

$$Z_o = \frac{q_{base}}{h_{base}}\frac{1}{\sqrt{g\propto}} \tag{5}$$

; where Z_o is the surge impedance ,$q_{base}$is the volumetric flow at the rated head (m^3/s), h_{base} is the rated head (m),g is the acceleration due to gravity (m/s^2), and$\propto$ is $\frac{f*LD}{2g}$.

The term Z_o can also be expressed using the water starting time constant (T_w), using expressions for the wave velocity and wave propagation speed:

$$T_w = Z_o T_e \tag{6}$$

$$Z_o = \frac{T_W}{T_e} \tag{7}$$

An analysis of the above equation can provide a good understanding of the phenomena involved in the hydraulic system of hydropower plants. The water starting time constant (T_w) is regarded as an inertia that is affected by a force producing an acceleration, and the penstock elastic time constant (T_e) is regarded as the time before a change in the flow conditions at the turbine, which are affecting the flow at the surge tank or reservoir. Because the change in flow is delayed, the flow at the start of the penstock will not be affected by a change in the flow at the turbine for a time period T_e. This indicates that, when the flow is decreased, the pressure at the turbine will increase, as the flow into the penstock is larger than the flow out of it; this is due to the delayed information on the flow conditions at the start of the penstock. Similarly, an increase in the gate opening will instantaneously decrease the pressure at the turbine.

A.3. Linear turbine model

The relationship between flow, speed, and efficiency is complex. The change in power, volumetric flow, and torque due to changes in speed, gate opening or head can be formulated as

$$dq = \frac{\partial q}{\partial n} n + \frac{\partial q}{\partial y} y + \frac{\partial q}{\partial h} h \tag{8}$$

$$dm = \frac{\partial m}{\partial n} n + \frac{\partial m}{\partial y} y + \frac{\partial m}{\partial h} h \tag{9}$$

$$dp = \frac{\partial p}{\partial n} n + \frac{\partial p}{\partial y} y + \frac{\partial p}{\partial h} h \tag{10}$$

; where q is the volumetric flow, y is the gate opening, n is the speed, h is the head at the turbine, m is the torque, and p is the mechanical power output. All parameters are given in per-unit denominations. The numerical values of the partial derivatives can be obtained from field measurements. To use the above turbine model, the calculations need to be done, as given in Table 2.

Table 2. Input Values of the Turbine Parameter Model used in the simulations

Parameters	Value
Rated head	819 m
Rated flow	142.5 m^3/s
Pressure wave propagation speed	1200 m/s
Acceleration due to gravity, a	9.79 m/ s^2
Headrace tunnel	
Length	23030 m
Diameter	6.8 m
Cross-sectional area	36.3 m^2
Steady-state frictional loss factor	0.06
Friction factor used in SIMPOW (FF_TUNNEL)	0.005
Water starting time (TWTUNNEL)	11.28 s
Surge tank	
Diameter	15 m
Cross-sectional area	176.63 m^2
Inflow loss factor	0.5
Inflow loss factor used in SIMPOW (FF_SURGE)	0.005
Storage constant, C_s	1015.15 s
Penstock	
Length	1078 m
Diameter	4 m
Cross-sectional area	12.56 m^2
Steady-state frictional loss factor (FF_PENSTOCK)	0.015
Water starting time, T_w	1.52 s
Elastic time constant, T_e	1.05
Surge impedance, Z_0	1.692

Apart from the parameters in Table 2, the additional parameters in Table 4 must be used for the simulation. The model is a linearized model, and the parameters used are given in Table 3.

Table 3. Additional Parameters of the Turbine Parameter Model

Parameter	Description	SIMPOW/DSL Code	Value used for simulation
$\frac{\partial q}{\partial y}$	Partial derivative of flow with respect to gate opening	EQY	0.64
$\frac{\partial q}{\partial x}$	Partial derivative of flow with respect to speed	EQX	–0.49
$\frac{\partial q}{\partial h}$	Partial derivative of flow with respect to head	EQH	0.37
$\frac{\partial m}{\partial y}$	Partial derivative of mechanical torque with respect to gate opening	EY	1.37
$\frac{\partial m}{\partial x}$	Partial derivative of mechanical torque with respect to speed	EX	–2.44
$\frac{\partial m}{\partial h}$	Partial derivative of mechanical torque with respect to head	EH	1.97

Note: The values were suggested by [5] and [10]

;m = mechanical torque; y = gate position; h = head; x = speed; q = volumetric flow.The above models are used in turbines T1 through T6, which are associated with generators G1 through G6 in figure 1.

A.4. Governor type DSLS/HYGOV/

This type of governor is available in the SIMPOW library [7]; it is a hydro-governor. This is the first part of the PSS/E-model HYGOV, and it contains the governor part. The block diagram is given in Figure 4.

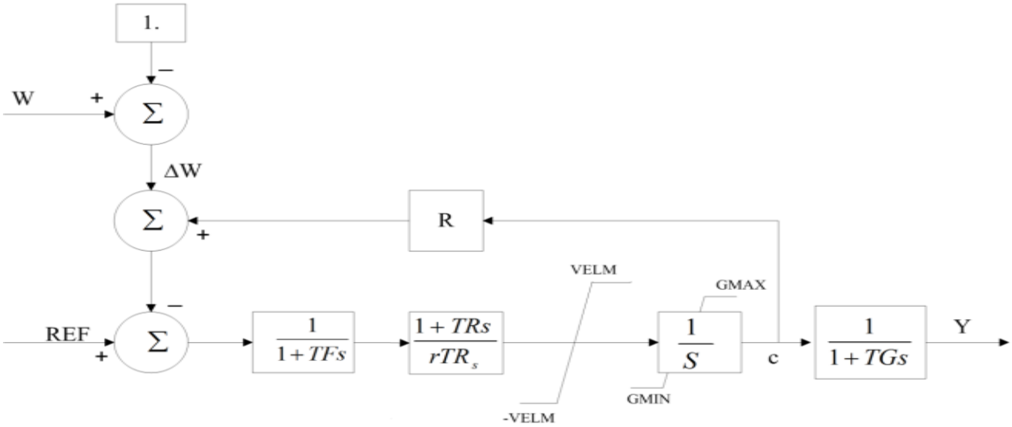

Figure 4. Block diagram of governor type DSLS/HYGOV/

;w = machine speed; Y = gate opening.

This type of governor is implemented for controlling the speed in all the generators (G1 through G9) of the stiff system and the weak system. The parameters of the governor are given in Table 4.

Table 4. Parameters of Governor Type DSLS/HYGOV/

Parameter	Legend	Value used for simulation
Permanent droop	RBIG n	0.04
Temporary droop	RSMALL n	0.4
Governor time constant (s)	TR n	8.0
Filter time constant (s)	TF n	0.05
Servo time constant (s)	TG n	0.2
Gate velocity limit	VELM n	0.2
Maximum gate limit	GMAX n	1.0
Minimum gate limit	GMIN n	0.0

3. Results and Discussion

In this section, we present the results obtained from the computer simulation for our analysis and discussion. We carried out studies of the effect of hydraulic system, hydro-turbine and governor parameters on transient and frequency stability for the grid-connected power system (Figure. 1).We identified the parameters of the hydraulic system, governor and turbine affecting the stability of power system and studied the effect of these parameters on a grid-connected power system.The single-line diagram of the grid-connected network is given in Figure.1. The following simulations were carried out. We performed a linear analysis which is integrated in SIMPOW to find the eigenvalues of the system. These eigenvalues provide information about the stability of the system and are useful when conducting system-stability studies. Our linear analysis techniques consist of the following:

A. Eigenvalue analysis

An eigenvalue is a system characteristic that describes a special dynamic behaviour of the system, called the mode. The eigenvalue may consist of a real and/or an imaginary part [1].
The real part indicates the damping of the mode. If the real part is positive, the system is un-damped and unstable, but if it is negative, the system is stable and the mode is damped.
The imaginary part indicates the swing of the mode. If the imaginary part is zero, the mode is non-oscillatory, but if it is non-zero, the mode oscillates.

Table 5. List of eigenvalues between 0.01 and 2 Hz

Eigenvalues Nos.	**Output Values**
24	(-1.0325 1/s, 1.6041 Hz)
46	(-1.0574 1/s, 0.38866 Hz)
48	(-1.0842 1/s, 0.39087 Hz)
61	(-1.1482 1/s, 0.39879 Hz)
63	(-1.1482 1/s, 0.39879 Hz)
65	(-1.1482 1/s, 0.39879 Hz)
67	(-1.1482 1/s, 0.39879 Hz)
69	(-1.1482 1/s, 0.39879 Hz)
71	(-0.28796 1/s, 0.073802 Hz)
73	(-0.24828 1/s, 0.065040 Hz)
75	(-0.19154 1/s, 0.053189 Hz)
77	(-0.19154 1/s, 0.053189 Hz)
79	(-0.19154 1/s, 0.053189 Hz)
81	(-0.19154 1/s, 0.053189 Hz)

We performed the linear analysis in SIMPOW for the grid-connected system and obtained a list of all eigenvalues. We observed that the real part of all the eigenvalues had a negative real part, so the system is stable. The eigenvalues with no imaginary part are not considered, as the associated mode will not oscillate. Only the eigenvalues with a frequency between 0.01 and 2 Hz are considered; they are given in Table 5.

B. Sensitivity analysis of governor parameters.

A sensitivity analysis tool is integrated into SIMPOW software and we used it to find out how much each component of the power system interacts with the oscillation of each eigenvalue. This tool can be used to investigate how various parameters of the turbine and governor influence various eigenvalues, including how sensitive the oscillation frequency is to changes in governor or turbine parameters [2], [3], [4] & [8].We performed a sensitivity analysis for the governor parameters of governor GOV1, which is associated with synchronous machine G1, and the simulation results obtained are similar to those of all other governors. The simulation results are given in Table 6.

Table 6. Sensitivity Analysis of Governor Parameters

Eigenvlaue No.	Parameters	Output Values
No. 42 (–0.93757 1/s, 1.3929Hz)	RBIG (permanent droop)	(-0.065308 1/s/unit, -0.019431 Hz/pu)
	RSMALL (temporary droop)	(-0.0066154 1/s/unit; 0.022555 Hz/unit)
	TF (Filter time constant)	0.45508 1/s/unit, -0.028121 Hz/unit)
	TG (Servo time constant)	(0.12721 1/s/unit, -0.041179 Hz/unit

From Table 6, we observed the following:

- The oscillation mode of eigenvalue No. 42(-0.93757 1/s, 1.3929 Hz) is sensitive to governor parameters RBIG (permanent droop), RSMALL (temporary droop), TF (filter time constant), and TG (servo time constant). This means that these governor parameters contribute to this eigenvalue.
- Eigenvalue No. 42(-0.93757 1/s, 1.3929 Hz) is less sensitive to all other parameters, including TR (governor time constant), VELM (gate velocity), GMAX (maximum gate limit), and GMIN (minimum gate limit), which means these governor parameters do not contribute to the oscillation of the eigenvalue.
- The oscillation modes of all other eigenvalues (numbers 24, 46, 48, 61, 63, 71, 73, 75, 77, 79, and 81) are less sensitive to all the governor parameters. This means that these governor parameters do not contribute to the eigenvalues listed above.

C. Sensitivity analysis of hydraulic parameters.

We carried out a sensitivity analysis of hydraulic parameters, and the simulation results are given in Table 7.

Table 7 shows that the following are true:

- The oscillation mode of eigenvalue No. 24 (–1.03251/s, 1.6041Hz) is sensitive to Z_0 (surge impedance) and less sensitive to all other hydraulic parameters.
- The oscillation mode of eigenvalue No. 42 (–0.937571/s,1.3929Hz) is sensitive to parameters FF_PENSTOCK (Friction factor of penstock), TE2 (Penstock elastic time constant), $\boldsymbol{Z_0}$ (surge impedance), EQH (partial derivative of flow with respect to head), EH (partial derivative of mechanical torque with respect to head),EY(partial derivative of mechanical torque with respect to gate opening) and EQY (partial derivative of flow with respect to gate

opening), and indicates contribution to the eigenvalue. This eigenvalue is less sensitive to other hydraulic parameters.

- All other eigenvalues are less sensitive to all hydraulic parameters.

After performing a linear analysis on the grid connected network, we performed transient stability studies. Here, a typical three-phase fault is applied to Bus B7 at time 1.000 s, and the fault is cleared at time 1.040 s by disconnecting line No.1 between Bus B7 and Bus B13.A graph showing the eigenvalues is given in figure 5.

Table 7. Sensitivity Analysis of hydraulic Parameters

Eigenvlaue No.	Parameters	Simulation Results
No. 24 (-1.0325 1/s, 1.6041 Hz)	Z_0	(-0.039493 1/s/unit, 0.0076156 Hz/unit)
No. 42 (-0.93757 1/s,1.3929 Hz)	FF_PENSTOCK	(0.079720 1/s/unit, -0.020163 Hz/unit)
	Te	(0.25285 1/s/unit, 0.010992 Hz/unit)
	$\mathbf{Z_0}$	(-0.039493 1/s/unit, 0.0076156 Hz/unit)
	EQH	(-0.096508 1/s/unit, 0.014125 Hz/unit)
	EH	(-0.015033 1/s/unit, 0.0036942 Hz/unit)
	EQY	(-0.015033 1/s/unit, 0.0036942 Hz/unit)

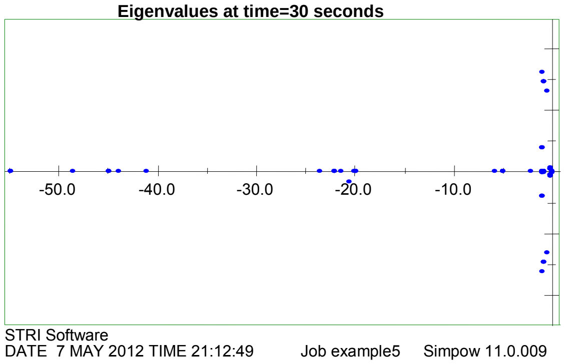

Figure 5. Graph showing eigenvalues.

All the eigenvalues have a negative real part, and the system is able to maintain stability after and during the post-fault state. We consider the electromechanical mode, and we take the eigenvalues of frequency 0.001 to 2 Hz; we calculate the damping ratios calculated, which are shown in Table 8.

Table 8. Calculation of Damping Ratios

Eigenvalues	Ω (rad/sec)	Damping ratio (ζ)
No. 24: (-1.03913 1/s, 1.60818 Hz)	10.099	10.23%
No. 26: (-0.840965 1/s, 1.46986 Hz)	9.231	9.07%
No.42: (-0.571116 1/s, 1.31023 Hz)	8.2282	6.92%
No.46: (-1.04838 1/s, 0.387099 Hz	2.431	39.60%
No.48: (-1.06900 1/s, 0.389844 Hz)	2.448	40.01%
No.55: (-1.14640 1/s, 0.398486 Hz)	2.502	41.65%
No.71: (-0.297208 1/s, 0.0735000 Hz)	0.462	54.10%

Based on Table 8, the damping ratios are fully acceptable, as they are above 5%; the system is well-damped.

4. Conclusion

We studied the impact of governor and hydraulic parameters on power-system stability of the grid connected network and the following conclusions can be drawn based on the simulations and analysis:

- Governor parameters such as permanent droop (RBIG), temporary droop (RSMALL), filter time constant (TF), and servo time constant (TG) affect the stability of the grid-connected power system network.
- Governor parameters such as governor time constant (TR), gate velocity (VELM), maximum gate limit (GMAX), and minimum gate limit (GMIN) do not affect the stability of the power grid connected power system
- The parameters of the hydraulic system affecting the network are surge impedance (Z_0), friction factor of penstock (FF_PENSTOCK), penstock elastic time constant (TE), partial derivative of flow with respect to head (EQH), partial derivative of mechanical torque with respect to head (EH), partial derivative of mechanical torque with respect to gate opening (EY), and partial derivative of flow with respect to gate opening (EQY).
- Hydraulic parameters such as storage constant of surge tank (CS), inflow loss factor of surge tank (FF_SURGE), friction factor of tunnel (FF_TUNNEL), water starting time of tunnel (TWTUNNEL), partial derivative of mechanical torque with respect to speed (EX), and partial derivative of mechanical torque with respect to gate opening (EY) do not affect the stability of the system.
- The damping ratios calculated for the transient stability studies are all above 5% and are all acceptable.

5. Acknowledgement

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