Droop Control of Hydro Power System in OpenHPL

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Abstract

OpenHPL is an open-source hydro power library for modeling, design, and analysis. Currently, OpenHPL consists of mechanistic models for waterways from a reservoir to tailrace, Francis and Pelton turbine models, a simple generator model, hydro power speed governor model, etc. However, the library lacks a *controller* for the parallel operation of hydro powers. This paper mainly focuses on extending OpenHPL with power-frequency droop control for a multi-generator system. Two simulation case studies are carried out for the parallel operation of hydro power units.

Keywords: Parallel operation of hydro powers, multi-generator system, Droop control, OpenHPL

1 Introduction

1.1 Background

Electricity generation from renewable sources is increasing because of oil insecurity, climatic concern, and the nuclear power debate. Renewable energy is a combination of intermittent and dispatchable energy sources. Intermittent sources like solar, wind, and tidal power plants exhibit fluctuating power production that creates an imbalance between generation and load. In this regard, renewable dispatchable sources like hydro power plants play a significant role in balancing out the variability caused by intermittent sources. Current hydro power modeling, design, and analysis tools are free or available commercially. Freely available tools include CASiMiR-Hydropower[1], LVTrans[2], and OpenHPL[3], while commercial tools include Alab[4] and Modelon Hydro Power Library (HPL)[5]. This drives a motivation for an open-source hydro power library development for modeling, design, and analysis.

A mechanistic model of hydropower systems had been developed in (Splavska et al., 2017) using mass and momentum balances which leads to a Modelica[6] based open-source hydropower library OpenHPL, and was initiated in a PhD study (Vytvytskyi, 2019). OpenHPL is under development at the University of South-Eastern Norway. Currently, OpenHPL has units for the flow of water in filled pipes (inelastic and elastic walls, incompressible and compressible water) (Vytvytsky and Lie, 2017), a mechanistic model of a Francis turbine (including design of turbine parameters) (Vytvytskyi and Lie, 2018), etc. The library is further extended with mechanistic models of different kinds of surge tanks and draft tubes (Pandey and Lie, 2020, Submitted). In addition, some accompanying work on analysis tools has been developed in scripting languages (Python, Julia) related to state estimation, structural analysis, etc (Vytvytskyi and Lie, 2019). The library has been tested on real power plant data (Pandey and Lie, 2020). The library can be interfaced with other Modelica libraries, for example, OpenIPSL[7] for generator and grid, PhotoVoltaics[8] for solar power plants, and WindPowerPlants[9] for wind power plants as in (Pandey et al., 2021; Pandey and Lie, 2020). However, the library lacks hydro power controllers for parallel operation of hydro power and load frequency control in an interconnected power system network.

In this regard, it is of interest to extend OpenHPL with hydro power controller models. This paper mainly focuses on developing a droop control mechanism applied for the parallel operation of hydro turbine generating units in OpenHPL.

1.2 Outline of the Paper

Section 2 presents a speed governing mechanism in a hydro power plant. Section 3 provides the concept of droop control in the parallel operation of hydro power plants. The implementation of droop control is tested via case-studies in Section 4. Finally, conclusions and future work are presented in Section 5.

2 Speed Governor for Single Hydro Power Plant

2.1 Governing mechanism

Figure 1 a) shows the speed governing mechanism in a hydro power plant. In the figure, T is the turbine, G is the generator and P_{g} is the generated power from the T-G aggregate which is supplied to cover the consumer load P_{ℓ}. When there is a difference in power generation and consumer load, the volumetric discharge $\dot{V}$ through the turbine is controlled which in turn controls the generation

[1]http://www.casimir-software.de/save_download.php?language=2

[2]http://svingentech.no/about%20lvtrans.html

[3]https://github.com/simulatino/OpenHPL

[4]http://www.alab.no/Alab-Hydropower-Software/Functionality-Alab-Hydropower-Software/Operation-simulation-with-waterway

[5]https://www.modelon.com/library/hydro-power-library/

[6]https://www.modelica.org/

[7]https://github.com/OpenIPSL/OpenIPSL

[8]https://github.com/christiankral/PhotoVoltaics

[9]https://github.com/christiankral/WindPowerPlants

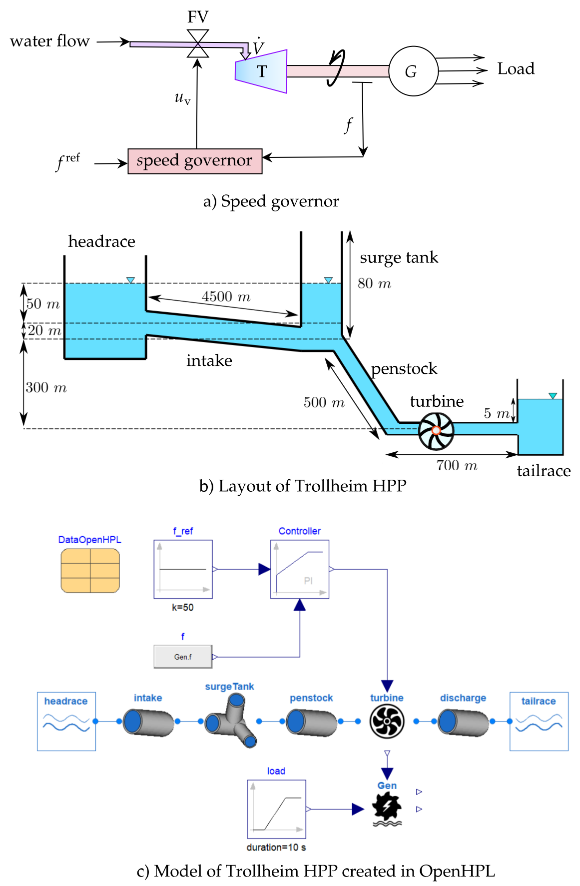


Figure 1. Speed governing in a hydro power system.

from the generator. To achieve this generation control, the shaft speed $\omega = 2\pi f$ of the T-G aggregate system is compared with the reference speed $\omega^{\text{ref}} = 2\pi f^{\text{ref}}$ by the speed governing system to generate a valve signal u_{v} for controlling the flow valve FV. It is of interest to design a speed governing system using a PI-controller in OpenHPL using a case study of a real hydro power plant.

2.2 Trollheim Hydro Power Plant

Figure 1 b) shows the layout of Trollheim hydro power plant (HPP) in Norway, with nominal power output 130 MW, nominal discharge rate 40 m/s^2, and nominal rated speed 380 rpm. The diameter of the intake tunnel is 7 m, and the diameter of both the surge tank and the penstock is 4 m. Figure 1 c) shows the model of Trollheim HPP created in OpenHPL. Models in OpenHPL are created simply by "dragging and dropping" hydro power units, and then connecting them together from the outlet of one unit to the inlet of another unit as in the case of the surge tank and the penstock shown in the figure. In Figure 1 c) a controller is used to maintain the frequency of T-G aggregate to $f^{\text{ref}} = 50$ Hz while controlling the flow through the turbine to balance the generation and the load. The controller is a PI controller taken from the built-in Modelica Standard Libraryand is characterized by a proportionality gain K_{p} and an integral time constant T_{i}.

2.3 Tuning of PI Controller

The PI controller is tuned based on the SMIC-PI tuning rule (Skogestad, 2001). In the SMIC-PI tuning method, a process is considered as a first-order system plus delay with a generalized transfer function as

$$G(s) = \frac{k}{\tau s + 1} e^{-\theta s}. \tag{1}$$

Controller parameters K_{p} and T_{i} are selected as

$$K_{\text{p}} = \frac{1}{k} \left(\frac{\tau}{\tau_{\text{c}} + \theta} \right) \tag{2}$$

$$T_{\text{i}} = \min\left(\tau, 4\left(\tau_{\text{c}} + \theta\right)\right) \tag{3}$$

where τ_{c} is considered as the tuning parameter and acts as a trade-off between (i) a fast controller response, and (ii) stability, robustness, and small input usage. For a reasonable response with good robustness we set $\tau_{\text{c}} = \theta$. In addition, the controller response becomes faster as the value of τ_{c} is decreased, and slower/smoother as the value of τ_{c} is increased.

2.4 Step Change in Load Power P_ℓ

Figure 2 shows the step responses from the PI controller for Trollheim HPP. The PI controller is specified by $K_{\text{p}} = 0.2$ and $T_{\text{i}} = 5$. Figure 2 shows the respective generated power P_{g} from the hydro power plant to balance the consumer load P_ℓ. Figure 2 also shows the turbine valve signal for controlling the water flow through the turbine to balance the load and the generation while maintaining the system frequency at 50 Hz.

3 Control of Multiple Hydro Power Plants

3.1 Problem Description

Next, consider operation of multiple hydro power plants connected to the same grid as shown in Figure 3 a), with generator i supplying power $P_{\text{g},i}$ to a common consumer load P_ℓ. For each of the T-G aggregates, what happens if we use the same speed governing mechanism as in Figure 1 a)? The grid frequency is determined by the "swing equation", essentially

$$J_{\text{eq}} \frac{d\omega}{dt} = \frac{1}{\omega} \left(\sum_i P_{\text{g},i} - P_\ell \right) \tag{4}$$

where ω is the common electric grid angular velocity related to frequency f by $\omega = 2\pi f$, and J_{eq} is the equivalent moment of inertia of all generators, referred to the electric grid frequency. If we use PI controllers as in Section 2, we essentially try to specify a single variable (f or ω) by changing many guide vane openings, one for each generator. This implies that we have many more unknowns (guide vane openings) than equations (specifying f or ω),and there is no unique solution. In practice, using

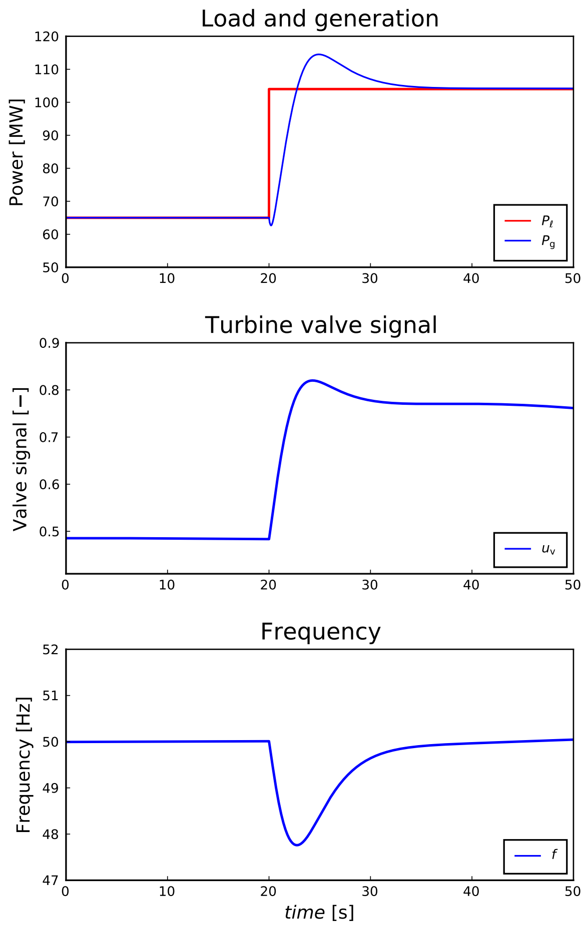


Figure 2. Step response from the PI controller for Trollheim HPP. a) Step change in load power P_ℓ from 50% loading to 80% loading and the corresponding generation P_g from the hydro turbine, b) turbine valve signal u_v, and c) frequency f of the plant.

one PI controller per generator will lead to wildly oscillating control outputs, and the system will break down (Schavemaker and Van der Sluis, 2017). In summary, we can only use one PI controller when controlling a single variable (the grid frequency). Thus a different strategy is needed for multiple generators.

In practice, the Transmission System Operator (TSO) makes a prediction of the next-day power consumption, P_ℓ^{ref}. In a competitive power market, power producers make a bidding on amount of power produced at a suggested price, and the TSO allots a share $P_{\ell,i}^{\mathrm{ref}}$ of the predicted power load to generator i (alternatively: to a power area i) such that $P_\ell^{\mathrm{ref}} = \sum_i P_{\ell,i}^{\mathrm{ref}}$.

The *real* next-day power load P_ℓ will differ from the predicted/reference power load P_ℓ^{ref} leading to a frequency f which differs from the reference frequency f^{ref} (typically 50 Hz or 60 Hz), and a mechanism is needed to distribute the difference $P_\ell - P_\ell^{\mathrm{ref}}$ among all the generators in a way which takes into account their capacity and drives f towards f^{ref}. This distribution of the difference is commonly done using a *droop control mechanism* as illustrated in Figure 3 a). The droop control mechanism can be

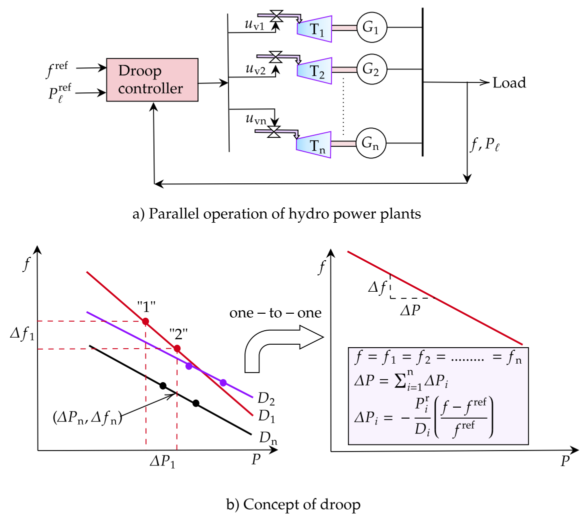


Figure 3. Concept of droop control for parallel operation of hydro power plants.

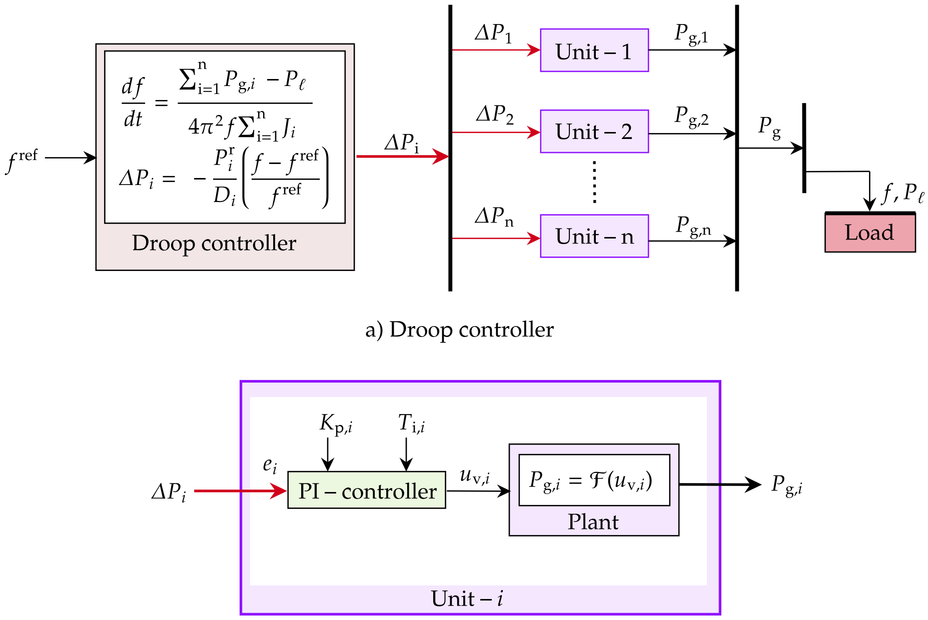
applied in diverse filed of engineering. Typical examples include the use of droop control in microgrid (Pota, 2013), inverters (Zhong and Zeng, 2016), oil and gas (Sharma et al., 2011), etc. The load power P_ℓ and the grid frequency f are compared with the reference load power P_ℓ^{ref} and the reference frequency f^{ref} . The droop controller makes a *one-to-one* power-frequency relation as in Figure 3 b) and distributes the proportioned signal to each of the generators' controller to restore the grid frequency. The droop controller operates based on the droop characteristics of each of the generators.

3.2 Concept of Droop Control

Figure 3b) shows the concept of the droop power-frequency control in a hydro power system. A droop is a slope of two independent variables in a dynamical system. For instance, the slope between the consumer P_ℓ and the frequency of the system f in a hydro turbine-generator power system can be represented by a power-frequency droop. When there is a sudden change of a consumer load there is a change in the system frequency. When the consumer load is greater than the generation, the system frequency decreases, and vice-versa. The droop D in case of power-frequency relation is expressed, thus, with the negative slope and defined as,

$$D = -\frac{\Delta f / f^{\mathrm{ref}}}{\Delta P / P^{\mathrm{r}}} \tag{5}$$

where f^{ref} and P^{r} are the reference frequency (normally taken as 50 Hz or 60 Hz depending on the power system network) and the rated power for the hydro power system, respectively. Δf is the change in frequency for the change in generation and load represented by ΔP. The values of the droop for a typical hydro power system are set in the range of $(2\% - 6\%)$.



b) Plant with PI controller

Figure 4. a) Internal structure of a droop controller b) Error from droop controller for the plant with PI-controller.

Figure 3b) shows the power-frequency characteristics or the droop characteristics for the operation of a multi-generator systems. The operation of the plant with droop characteristics D_1 at position "1" is shifted to position "2" when the consumer load changes suddenly by ΔP_1 with a drop in frequency Δf_1; and so on for the other systems with droop characteristics $D_2, D_3, \ldots.D_n$. The relationship between droop characteristics of each of the parallelly ran multi-generator systems is transferred into one-to-one $P-f$ relation. In the figure, ΔP is the overall difference in the generation and the load which is distributed to each of the generators for restoring f from the droop controller. The generation to be increased by the i^{th} generator to cope with the total variation ΔP in the multi-generator system, is given as,

$$\Delta P_i = -\frac{P_i^{r}}{D_i}\left(\frac{f - f^{\mathrm{ref}}}{f^{\mathrm{ref}}}\right). \tag{6}$$

3.3 Internal Structure of Droop Controller

Figure 4 a) shows the internal structure of a droop controller. The grid frequency f is calculated based on the measurement available for the generation $P_{g,i}$ and the load P_ℓ using the swing equation. For each of the generators, based on the droop D_i, power rating P_i^{r} and the grid frequency f, an error signal ΔP_i is generated for the PI controller of the generator which is used to change the guide vane opening of the hydro turbine as shown in Figure 4 b) which drives the grid frequency f towards f^{ref}.

Table 1. Parallel operation of two turbines for Trollheim HPP.

Units	P^{r}	D	K_p	T_i
Unit-1	65 MW	4%	0.03	3
Unit-2	65 MW	5%	0.03	3

4 Case Studies

4.1 Case Study-1

We now consider Trollheim HPP with two hydro turbine units operating in parallel for supplying to a common consumer load P_ℓ. The droop, rated power, and values of K_p and T_i are given in Table 1.

Figure 5 a) shows the total load and the generation from the hydro power units. In the figure, at time = 30 s load is increased from 65 MW to 90 MW. To compensate the increase in 25 MW load, according to Eq. (6), Unit-1 should produce $\frac{D_2}{D_1+D_2}\Delta P = \frac{5}{4+5}\cdot 25 \approx 14$ MW and Unit-2 should then produce ≈ 11 MW as shown in the figure. As the generating Unit-1 has a lower droop than Unit-2, Unit-1 will add more power into the grid according to Eq. (6). Figure 5 b) shows the turbine valve signal for both the hydro power units. Figure 5c) shows the grid frequency and frequencies of both synchronous generating units. As the consumer load increases, the grid frequency of the system decreases and to compensate for the increased power both flow in the turbine units should be increased which will accelerate the generators of Unit-1 and Unit-2. The frequency of generators and the grid will be the same after the steady-state condition is reached.

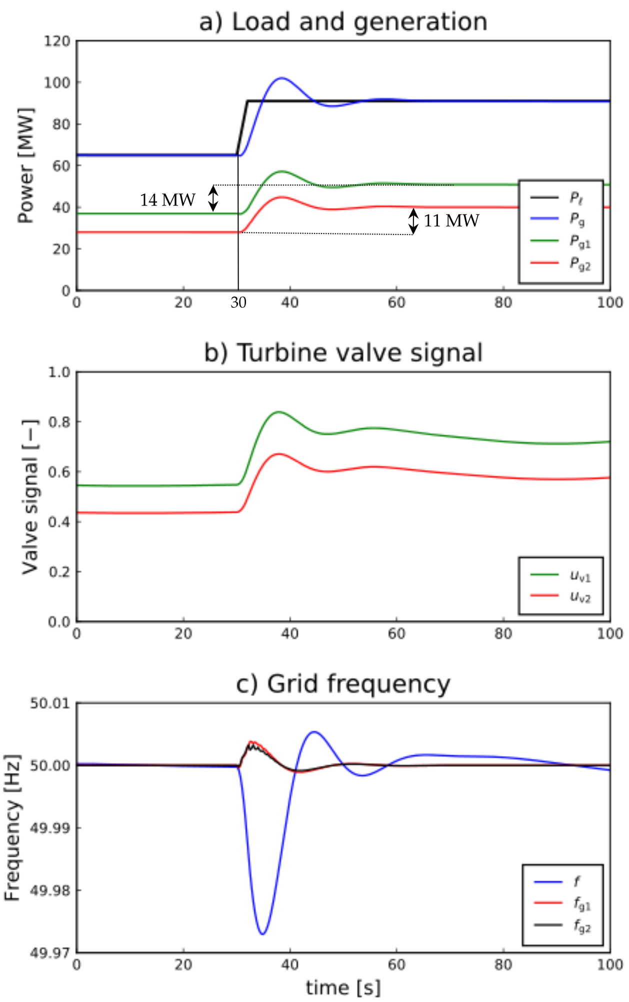
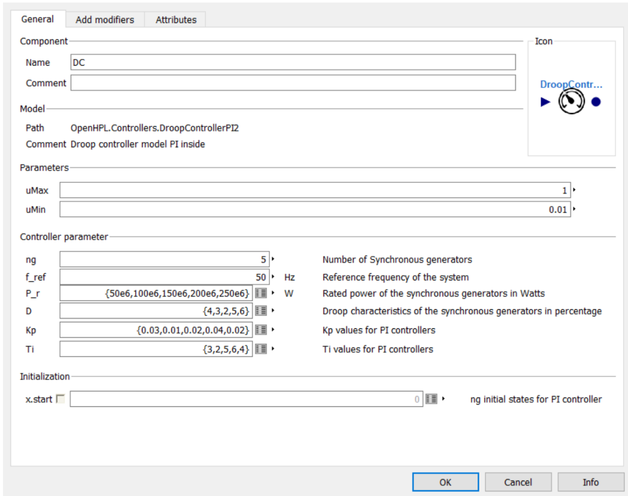
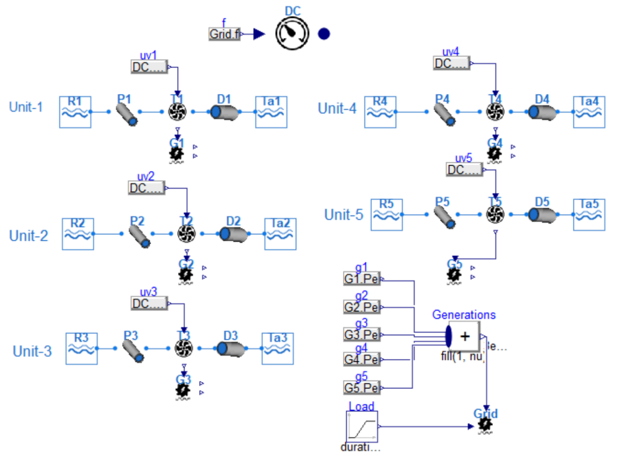


Figure 5. Droop control for parallel operation of two hydro units for Trollheim HPP.



a) Parameters for droop control in OpenHPL



b) Models of parallel operation of five hydro power plants in OpenHPL with droop control

Figure 6. Droop control in OpenHPL.

4.2 Case Study-2

We now consider models of five hydro power plants operating in parallel to supply a common consumer load as shown in Figure 6 b). Figure 6 a) shows the initialization and droop controller parameter GUI in OpenHPL. For the icon shown in the top-right of the figure, the input to the controller is the grid frequency f and output from the controller is the turbine valve signal u_v. To initialize the droop control for n number of synchronous generators, rated power P^r, droop D, K_p and T_i values for PI-controller for each of the turbine-generator plant should be given as in Figure 6 a). For the purpose of the case study, P^r, D, and K_p and T_i values for the PI-controller for five hydro power plants are given in Table 2.

Figure 7 a) shows the generation and load in the case of five hydro power plants operating in parallel. Figure 7 b) shows the respective generation from each of the hydro power units supplying to balance the difference in the load and the generation. The generation from each of the hydro power units are distributed based on their power rating and droop characteristics. In the figure, Unit-1 has the least contribution and Unit-4 has the highest contribution to balance the generation and the load. Figure 7 c) shows the turbine valve signals for controlling flow through each of the turbine units. From the figure we can see that to cope with the load and the generation variation flow through Unit-3 is the highest and flow through Unit-1 is the least. The flow $u_{\mathrm{v},i}$ depends on D_i, $K_{\mathrm{p},i}$ and $T_{\mathrm{i},i}$. Similarly, 7 d) shows the grid frequency and frequencies of each of the generator units supplying to a common consumer load.

From Figure 4 b) we see that if $T = \sum_{i=1}^{5} T_{\mathrm{i},i}$ is the equivalent integral time constant at which the grid frequency of the system is restored then the valve signal for the units are given as

$$u_{\mathrm{v},i} = K_{\mathrm{p},i}\Delta P_i + \frac{K_{\mathrm{p},i}}{T_{\mathrm{i},i}} \int_0^T \Delta P_i dt \tag{7}$$

where

$$\Delta P_i = -\frac{P_i^\mathrm{r}}{D_i}\left(\frac{\Delta f}{f^\mathrm{ref}}\right). \tag{8}$$

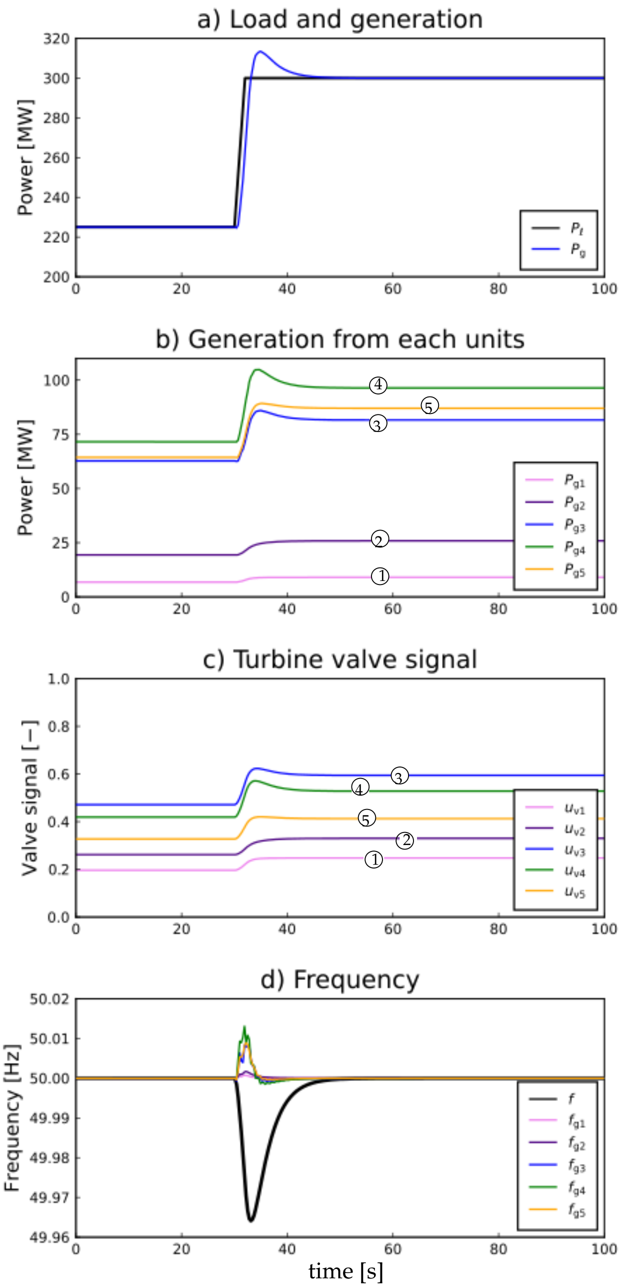


Figure 7. Droop control for five generators operating in parallel index by numbers from 1 to 5.

Table 2. Specifications of power plants.

P^r	D	K_p	T_i
50 MW	4%	0.03	3
100 MW	3%	0.01	2
150 MW	2%	0.02	5
200 MW	5%	0.04	6
250 MW	6%	0.02	4

Table 3. Valve signal and power shared after the steady state is reached at sudden increment in the load power.

$u_{v,i}$	$\Delta u_{v,i}$	ΔP_i
0.23	0.03	2 MW
0.3	0.04	5 MW
0.6	0.13	16 MW
0.55	0.12	27 MW
0.4	0.03	25 MW
		$\sum \Delta P_i = 75\,\mathrm{MW}$

Putting Equation (8) into (9) we get

$$u_{v,i} = K_{p,i}\left(1 + \frac{1}{\frac{T_{i,i}}{T}}\right)\Delta P_i$$

which can be further expressed as

$$u_{v,i} = -K_{p,i}\left(1 + \frac{1}{\frac{T_{i,i}}{T}}\right)\left(\frac{P_i^r}{D_i}\frac{\Delta f}{f^{ref}}\right) \qquad (9)$$

where $\frac{T_{i,i}}{T}$ is the integral time constant for the valve signal $u_{v,i}$ and depends on total integral time constant given by $T = \sum_{i=1}^{5} T_{i,i}$. This adheres that as the number of hydro turbine increases the plant with a lower value of T_i will have a smooth control over u_v as shown in Figure 7 c).

From Figure 7 d) f is the grid frequency. Figure 7 a) shows that at $t = 30$ s the load power P_ℓ increases from 225 MW to 300 MW with an increment of 75 MW. This addition of the load will be sensed by the decrement in the grid frequency as shown in Figure 7 d) where f is the grid frequency. From Figure 7 d) we see that in response to the addition of the load into the grid there is a change in the grid frequency given as $\Delta f \approx 0.037$ Hz. With $T = \sum_{i=1}^{5} T_{i,i} = 20$ s and the values taken from Table 2 for all the generators, the required valve signal for each of the hydro turbines can be calculated from Equation (9). The steady state values of the valve signal $u_{v,i}$ after the grid frequency is restored is given in Table 3. Similarly, the power shared among the generators shown in Figure 7 b) is also given in Table 3.

5 Conclusions and Future Work

This paper presents the droop control mechanism applied for the parallel operation of hydro power plants for an open-source hydro power library OpenHPL. The droop controller is a feature extension for OpenHPL. The difference in total generation and load is shared among all the generators operated in parallel to cope with the difference. This is achieved by controlling the flow through the turbines. For an i^{th} generator operating in parallel in a multi-generator system, the turbine valve control signal depends particularly on K_p and T_i of the PI-controller for that unit, power rating P^r, the droop D and the total integral time constant $T = \sum_i T_{i,i}$.

Future work includes an extension of OpenHPL with automatic generation control (AGC) or load frequency control (LFC) in the case of the interconnected power system network.

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