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Dynamic model for control of Variable Speed Hydropower Plant

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Abstract

With the popularity and use of s-domain models for control, time-domain models have been less worked upon. Easy availability of methods to solve ordinary differential equations (ODEs) and differential algebraic equations (DAEs) makes it possible to work directly with the time-domain models nowadays. This would provide the flexibility and model structure for various non-linear analysis and implementation of modern control schemes. This paper presents a detailed time-domain model of variable speed hydro power plant suitable for control, including the hydraulic and electric parts up to the grid. The converter configuration used on the grid side is replaced by a virtual synchronous generator considering only active power control. The model is simulated for step and ramp load changes and together with the governing action. Results show that the upstream water oscillation and pressure imbalance dynamics depends on the size of load change. The ramp load change seems to have more smooth operation on the upstream side. Furthermore, the turbine speed is allowed to deviate away from its reference value for a while. This opens the possibility of utilizing the rotational energy in the turbine generator unit with properly controlled output power without causing the small signal instability in upstream side. Also, it is possible to provide the ancillary services to the grid using this model and controlling it as required.

Keywords: grid,variable speed hydropower, dynamic model for control, virtual synchronous generator frequency, ancillary services

1 Introduction

Variable Speed Hydro powers(VSHPs) have the capability to utilize the kinetic energy in Turbine for instant power delivery to the grid enabling them to provide the additional ancillary services for grid support including frequency and voltage support. The ability of VSHPs to deviate temporarily from rated speed to quickly vary the output power with minimum possible disturbance in grid frequency, using converter technology makes them more popular alternatives as flexible power sources (Valavi and Nysveen (2016)). The converter instantly adjusts output power as required, governor then acts according to the output power provided to the grid, and adjust turbine power within few minutes Reigstad and Uhlen (2020a). The usage of Converter Fed Synchronous Machines (CFSM) to operate the hydro powers in full power range also helps to improve the efficiency of operation of Hydro power plants (HPPs). VSHPs have mostly been attractive in the field of hydro power since last decade. Using the concepts of converter fed machines (both synchronous and induction), operating hydro power in variable speed has been very common practice in USA and Europe (Shao et al. (2021),seydouxAcosta et al. (2020),Bortoni et al. (2019)). Unlike the induction machines, con-

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verter fed synchronous machine (CFSM) implements a full size converter which enables us to operate the hydro power plant in any range of power as needed making it more flexible.

(Gao et al. (2021)) in their work have developed a model for VSHP capable of operating in full power range. With the use of hydraulic turbine model and Permanent magnet synchronous generator, they have proposed multi-objective control method along with comparison with a normal hydro power plant and found out a considerable increase in energy production in variable speed operation (VSO) mode. Similarly, in (Guo et al. (2018)), an improved modelling approach with turbines having Hill-chart efficiency characteristics is proposed, where we find component-wise model of upstream hydraulic system and the turbine and generator model for a micro-hydro power plant. With experimental validation, it is shown that the operation in VSO mode enables us to obtain more power from turbine and even allows us to have control on the grid side effectively. Moreover, the authors in (Huang et al. (2023)) provide a model for variable speed Pump Storage plant (PSH) which represents the hydraulic system using continuity equation which involves solving partial differential equation and implements Doubly-fed Induction Generator (DFIG). Looking at more recent works, studies about water-saving with increased efficiency in power production (Presas et al. (2023)), flexible operating conditions in variable speed hydraulic turbines for PSH along with maximizing grid benefits(Seydoux (2024)), mathematical modelling with focus on the dynamics of turbine (Ramos et al. (2023)), etc have been done in the past year with refined turbine models for improving the operation of VSHPs. They take into account the internal details of turbine model and their impact on VSHP operation. Looking at the trend of modelling, the VSHP models are either developed focusing on functional details of a particular component or region. For example, researchers working on the upstream side (water ways) and turbine focus only on the hydraulic dynamics while research on the electrical side focus only on the generator dynamics and grid side modelling. A complete representation of VSHP including both hydraulic components, turbine, generator, converter and the grid is lacking.

A complete model of VSHP for grid integration studies is given by the authors in (Reigstad and Uhlen (2020a)) who propose hydraulic model based on Euler turbine equations. This paper compares various turbine models depending on the dynamic performance of VSHP including water hammer losses, surge tank behaviours, etc. Furthermore, the same author combines a converter model with this hydraulic model proposing a complete VSHP model in (Reigstad and Uhlen (2020b)) and simulates this in Kundur two area model. The converter uses dq frame to control the output voltages and inject the power to the grid in required frequency even when the turbine speed deviates from the rated one. This model has been used for control and grid support studies by the author in their further works. A drawback of the VSHP model by Reigstad and Uhlen (2020a, 2020b) is that the majority of the VSHP components are modelled in the s-domain that only represents linear dynamics.

As a matter of fact, from the literature, we found that s-domain representation for VSHPs (both hydraulic and electric side) are more popular from the past which align with most of the classical control schemes like the PID controllers. In frequency domain or what we call as transfer function models, often parameters are lumped together to form a composite parameter which may lack real world physical interpretation. Most importantly, transfer function models in s-domain are linear in nature and hence non-linearities are completely neglected. However, it would be interesting to look at actual parameter values and their possible variations or study about parametric uncertainty for model based controllers, if we could use them directly in time-domain (t-domain). In addition, time-domain models can be nonlinear in nature. With the easy availability of methods to solve Ordinary Differential Equations (ODEs) and (Differential Algebraic Equations (DAEs), time domain models for VSHP would provide the flexibility and model structure to perform various nonlinear analysis. In addition to this, a time domain model of VSHP is highly suitable for implementing modern control schemes like non-linear stochastic Model predictive Control (S-MPC). To fill up the gap, in this paper, a complete model of VSHP in time domain is developed. It includes both the hydraulic side (water ways including turbine, penstock, surge tank, conduict etc.), and also the electrical side that includes virtual synchronous generator, converter and grid. This paper proposes a mathematical model for VSHP in the form of (ODEs) and algebraic equations in a component wise fashion which is suitable to be used for control purpose.

Model details are presented in Section 2 for each component involved in a VSHP. Similarly, section 3 presents simulation cases with brief discussion on the results. And finally, section 4 presents conclusions from the paper along with possible future work.

2 Model Details

Figure 1 shows overall block diagram of a VSHP which represents all the components involved and their linkage. Each component is explained in detail in the sub-

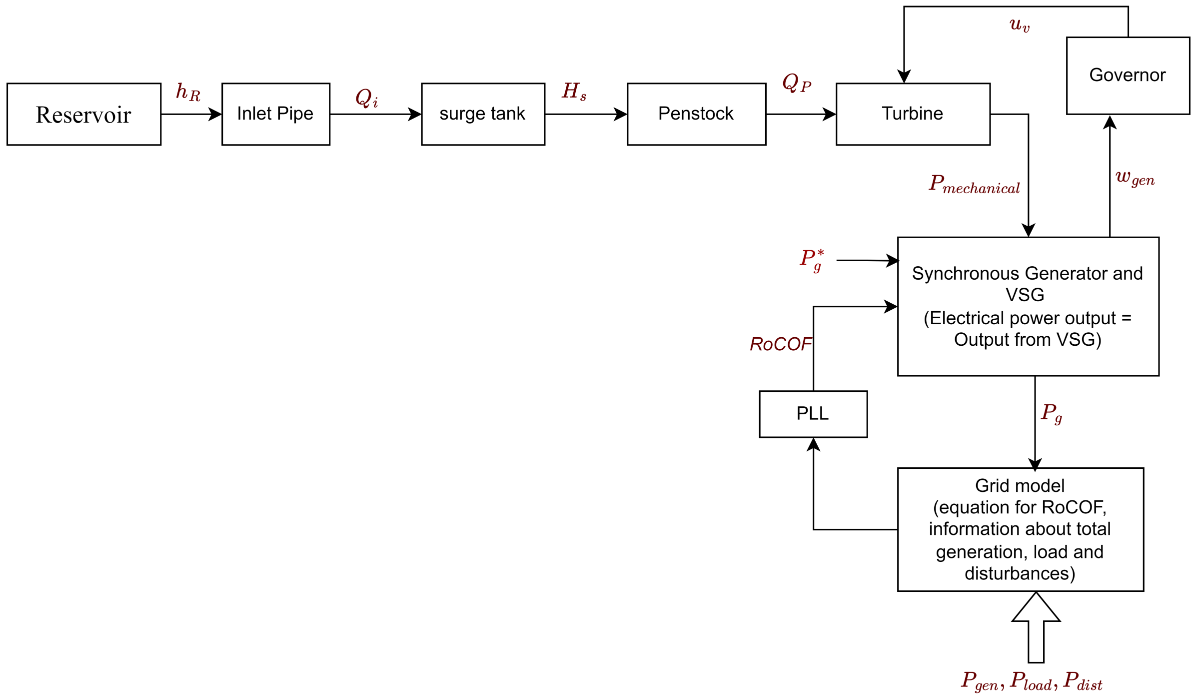

Figure 1: Block diagram showing component wise representation of a VSHP

sections to follow.

The hydraulic part is represented based on mass and momentum balances and each component equations are derived based on (Lie (2019)). The model of the electric part is taken from existing books and past publications. Electrical system is preferably represented in per unit (pu) for the ease of analysis. In this paper, generator, VSG and the grid are represented in pu system. The mechanical power generated by the turbine is converted to pu value using the base value of mechanical power, and is injected to the generator.

2.1 Reservoir

The reservoir is represented as open pond as shown in Figure 2. For simplicity, the reservoir is assumed to be very large, and thus the level of water in the reservoir is assumed to be constant.

The pressure at the bottom of the reservoir is the sum of atmospheric pressure and the hydrostatic pressure due to water column in the dam, i.e.

$$P_{atm} + \rho g h_R = P_{R,2} \tag{1}$$

where,
P_{R2} = Pressure at the bottom of reservoir
P_{atm} = Atomspheric pressure
g = acceleration due to gravity
h_R = water level in reservoir
ρ = Density of water

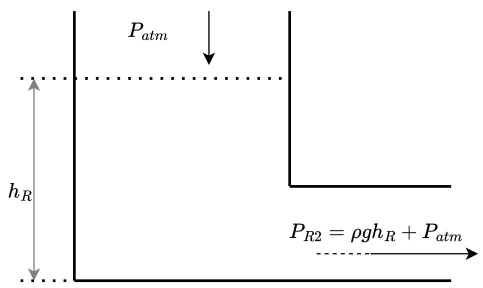

Figure 2: Schematic representation for model of dam with constant water level

2.2 Inlet Race

A schematic of the inlet pipe is shown in Figure 3. For simplicity, the flow in the inlet race is considered to be a full pipe flow. Since mass is constant inside a conduit,with this assumption, the mass is assumed to be balanced. The outflow from the reservoir will be the inflow to the inlet race.

For the momentum balance, the forces acting on the conduit or inlet race are

$$F_i = F_{i,p} + F_{i,g} - F_{i,f}$$

where,
$F_{i,p}$=Force due to pressure
$F_{i,g}$=Force due to gravity
$F_{i,f}$= Friction loss

Also, we may write

$$F_{i,P} = P_{i,1}A_i - P_{i,2}A_i$$
$$F_{i,g} = m_i g\frac{H_i}{L_i}$$
$$F_{i,f} = \frac{K_i^m A_{i,w} f_{i,D}}{4}$$
$$A_{i,w} = \pi D_i L_i$$
$$K_i^m = \frac{\rho Q_i|Q_i|}{2A_i^2}$$

With all these forces considered, the final equation for the flow in inlet pipe, may be written as:

$$\frac{dQ_i}{dt} = \frac{A_i}{\rho L_i}(P_{R2} - P_{s,1}) - \frac{\pi D_i f}{8A_i^2}Q_i|Q_i| + \frac{gA_iH_i}{L_i} \quad (2)$$

Here,
$P_{R2} = P_{atm} + \rho g h_R$
$P_{s,1} = \rho g H_s + P_{atm}$

where,
A_i = Cross section area of inlet pipe
L_i = Length of inlet pipe
D_i = Diameter of inlet race pipe
f = Coefficient of friction
Q_i = flow in inlet pipe
A_i = surface area of inlet race pipe
$A_{i,w}$ = wetted area of inlet race
H_i = Vertical height of inlet pipe (height difference between starting and end point)

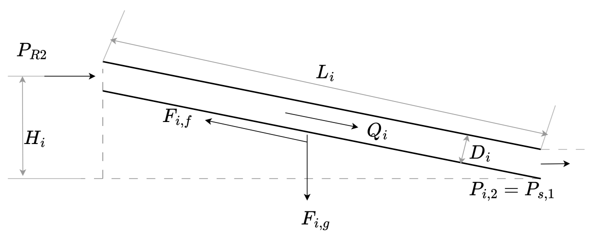

Figure 3: Schematic representation for model of inlet pipe

2.3 Surge Tank

A schematic of the surge tank is shown in Figure 4.

Pressure balance:

$$P_{s,1} - \Delta P_s = P_{s,2}$$
$$P_{s,2} = P_{atm}$$
$$\Delta P_s = \rho g H_s$$

Mass balance:

$$\dot{m}_{s,i} = \rho Q_s$$

Momentum balance:

$$\dot{\mu}_s = \dot{\mu}_{s,i} + F_s$$
$$\mu_s = \frac{m_s Q_s}{A_s}$$
$$m_s = \rho V_s$$
$$V_s = \pi r_s^2 l_s$$
$$\dot{M}_{s,i} = \dot{m}_{s,i} v = \rho Q_s \frac{Q_s}{A_s}$$

Forces acting in the surge tank

$$F_s = F_{s,p} - F_{s,g} - F_{s,f}$$

where,
$F_{s,p}$=Force due to pressure
$F_{s,g}$=Force due to gravity
$F_{s,f}$= Friction loss

The mass balance and pressure balance lead to the equation for height of surge tank which can be written as:

$$\frac{dH_s}{dt} = \frac{Q_s}{A_s} \quad (3)$$

Here,

$$Q_s = Q_i - Q_P \quad (4)$$

where,
Q_s = Flow in surge tank
Q_P = Flow in penstock
H_s = water level in surge tank
A_s = Surface area of surge tank

2.4 Penstock

Assuming no leakage through the penstock piping system, the in-fluent mass flow is equal to the effluent one

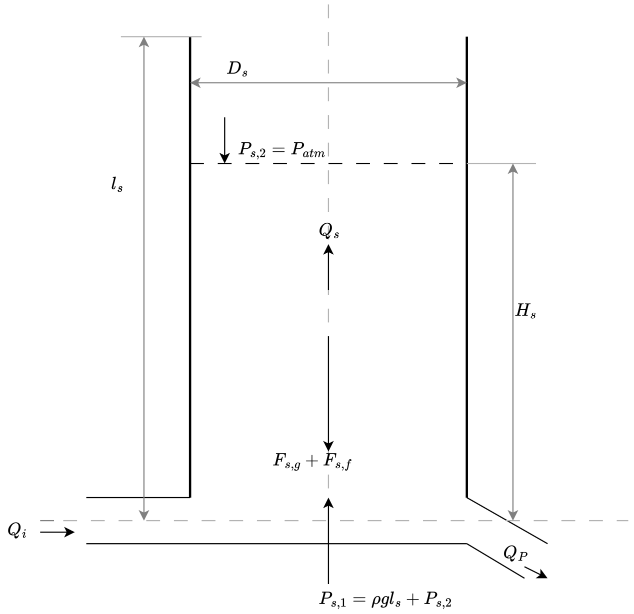

Figure 4: Schematic representation for model of surge tank

so that the mass is balanced. A schematic of the penstock is shown in Figure 5.
The forces acting on the penstock are

$$F_P = F_{P,p} + F_{P,g} - F_{P,f}$$

where,
$F_{P,p}$=Force due to pressure
$F_{P,g}$=Force due to gravity
$F_{P,f}$= Friction loss

The values of these forces are derived the same way as in inlet pipe. With all these forces considered, the final equation derived is for the flow in penstock, which may be written as:

$$\frac{dQ_P}{dt} = \frac{A_P}{\rho L_P}(P_{s,1} - P_t) - \frac{\pi D_P f}{8A_P^2} Q_P|Q_P| + \frac{g A_P H_P}{L_P} \tag{5}$$

Here,

$$P_t = Pa(1 + \left(\frac{Q_p}{C_v u_v}\right)^2$$

where,
A_P = Cross section area of penstock
L_P = Length of penstock
D_P = Diameter of penstock
H_p = Vertical height of penstock
P_t = Pressure in Turbine
Q_P = Flow in penstock

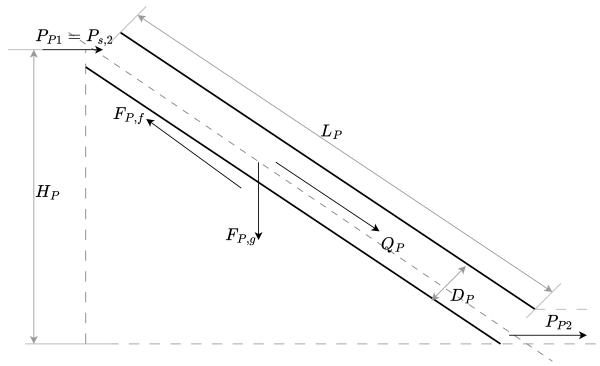

Figure 5: Schematic representation for model of penstock

2.5 Turbine

A Francis turbine model based on Euler's turbine equations is used in (Lie (2019)). The Francis turbine is a radial flow turbine which experiences the flow pattern based on guide vanes mechanism and pressure drop across it. The section from the end of penstock to the end of draft tube as a whole is taken as a turbine here. Also, the details of guide vane pressure drop is implicitly neglected and the pressure drop (ΔP_v) is modelled as some standard valve model. Thus the equation of pressure drop may be written as:

$$\Delta P_v = P_t - P_{atm} = P_{atm}\left(\frac{Q_p}{C_v u_v}\right)^2 \tag{6}$$

The equation for produced mechanical shaft power is derived as in Lie (2019) taking the nominal values of flow, head and grid frequency as given in the appendix.

$$P_{shaft/mechanical} = \dot{m}wR_1\left[\frac{Q_p}{A_1}Cot\alpha_1\right] - \dot{m}wR_2\left[wR_2 + \frac{Q_p}{A_2}Cot\beta_2\right] \tag{7}$$

The total work removed through the turbine is the sum of shaft mechanical power and the losses which may be written as:

$$P_{total} = P_{shaft/mechanical} + P_{f1} + P_{f2} \tag{8}$$

Where, P_{f1} is friction loss from turbine entrance and through the guide vanes which is neglected here and P_{f2} is shock and swirl loss.

$$P_{f2} = k_{f2,1}Q_p(cot\gamma_1 - cot\beta_1)^2 + k_{f2,2}Q_p cot^2\alpha_2 + k_{f2,3}Q_p^2$$

$$cot\gamma_1 = cot\alpha_1 - \left(\frac{wR_1}{Q_p/A_1}\right)$$

$$cot\alpha_2 = cot\beta_2 + \left(\frac{wR_2}{Q_p/A_2}\right)$$

And finally, turbine efficiency may be calculated as:

$$\eta_{turbine} = \left(\frac{P_{shaft/mechanical}}{P_{total}}\right) \quad (9)$$

where,
ΔP_v = Pressure drop across the turbine
u_v = Gate opening
C_v = Turbine valve capacity (nominal information of hydro-turbine system)
$P_{shaft/mechanical}$ = Mechanical power output given by turbine
w = Speed of turbine-generator unit
$\eta_{turbine}$ = Turbine efficiency
R_1 = Inlet radius
R_2 = Outlet radius
w_1 = Inlet width
k_1 = opening degree of turbine
α_1 = guide vanes opening

2.6 Governor

Governor is used to maintain the speed of VSHP at the rated value by operating the guide vanes, after it has undergone load changes. Although can be run in variable speeds, the VSHP when operated in grid connected configuration, needs to follow the grid frequency during the steady state operation. The governor acts as a local controller to maintain this. Here, the governor without droop is implemented as a simple feedback control scheme using PI controller. The set-point for governor is taken as the grid frequency so as to maintain the turbine rotating speed to synchronous value. Furthermore, the set point for guide vanes can directly be generated from the control schemes like MPC or robust control schemes which receive load demand from the grid as reference and operate the gate or guide vanes as required for the coordinated control of VSHP. The equation of governing scheme used here may be written as:

$$u_v = K_p(w^* - w) + \frac{1}{K_i}\int(w^* - w) \quad (10)$$

Where,
w^* = reference frequency (speed) for turbine-generator unit (taken from the grid for grid connected configuration)
w = speed of turbine-genertaor unit

2.7 Synchronous Generator

A fourth or sixth order synchronous generator model can be used as a detailed model when the focus is on the integration of the generator equations with the converter model and excitation model. However, in this work, the generator model used is simply represented as swing equation since we are only looking at injection of active power via the concept of Virtual Synchronous generator (VSG) to the grid. More details about VSG can be found at (Machowski et al. (2011)).
Equation for the generator used here can be written as:

$$w_{gen} = \Delta w_{gen} + w_{grid} \quad (11)$$

$$\frac{d\Delta w_{gen}}{dt} = \frac{1}{2Hw_{gen}}(P_m - P_g - D\Delta w_{gen}) \quad (12)$$

where,
$P_m = P_{shaft/mechanical}$ / Mechanical power base value
P_g = Electrical power injected by the VSHP to the grid (pu)
H = Moment of inertia
w_{gen} = Frequency of turbine- generator unit
Δw_{gen} = Change in frequency of generator
D = Damping coefficient
w_{grid} = Grid frequency

2.8 Converter and Grid

Virtual Synchronous generator (VSG)
(Reigstad and Uhlen (2021)) and (Reigstad and Uhlen (2019)) have presented comparative study of five virtual Inertia (VI) Control Schemes applicable to VSHPs and concluded that the VSG based VI control scheme has best perfomance from grid support point of view. The comparative evaluation further suggested VSG because it was found that VSG based scheme is able to provide both inertial response and frequency containment, has shortest response time and can reduce maximum deviation in grid frequency, is less impacted by power oscillations and the hydraulic transient behaviour is more or less similar for all VI schemes. So, the equation of VSG is taken in the same way as done in (Reigstad and Uhlen (2019)). Among the two converters present in a VSHP, only the outer loop control of grid side converter is taken and equation of VSG is

derived. Only outer loop control can be taken to simplify the converter equations because the dynamics of inner controller is generally faster than the step length of predictive controllers to be used. The equation may be written as:

$$P_g = K_{VSG,p}\Delta w_{grid} + K_{VSG,d}\frac{d\Delta w_{grid}}{dt} + P_g^* \quad (13)$$

where,
P_g = Electrical power injected by the VSHP to the grid (pu)
Δw_{grid} = frequency change of grid(pu)
P_g^* = Reference value of the electrical power for VSHP system (pu)
$K_{VSG,p}$ = Proportional time constant for VSG control loop
$K_{VSG,d}$ = Derivative time constant for VSG control loop

Grid Model
The grid is modelled as a large synchronous generator which can be represented by a swing equation (Kundur et al. (1994)). If there are multiple sources of active power connected to the grid, P_{gen} is the sum of all sources of active power. But, here only one source is assumed to be connected to the grid, and so P_{gen} is the power given by VSHP only. The equation used here may be written as follows

$$\frac{d\Delta w_{grid}}{dt} = \frac{w_{ref}}{2H_g S_n}(P_{gen} - P_{load} + P_{dist} - D_m\Delta w_{grid}) \quad (14)$$

$$w_{grid} = w_{ref} + \Delta w_{grid} \quad (15)$$

where,
P_{gen} = Total active power generation in the grid (pu)
P_{load} = Total active power demanded by the grid (pu)
w_{ref} = Reference frequency for the grid
P_{dist} = Any other disturbances or power imbalances in the grid
D_m = Damping coefficient for the grid
w_{grid} = Grid frequency
H_g = Mean grid inertia
S_n = Total rated power of all connected sources

3 Simulation results

The model is simulated for following cases:

3.1 Openloop simulation without governing action

The openloop simulation of VSHP system for small load change results in frequency variation of generator

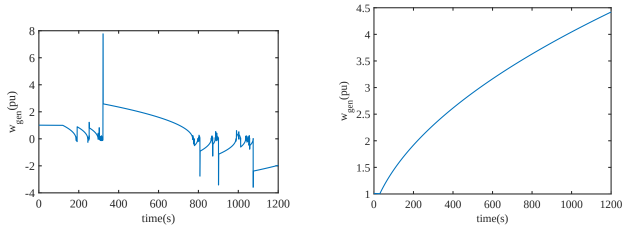

Figure (a) Figure (b)

Figure 6: Generator frequency for small load change without governor: (a)load increased (b)load decreased

outside the viable range as seen in figure 6 . According to the standards, the highest allowable frequency variation for Nordic grid is ± 1000 milli Hertz, which makes only 2% of the rated value (Fingrid (2022)). This limits the generator frequency swing accordingly, to remain synchronized. But, in this case, the deviation is out of the allowable range, which would make the generator lose synchronism with the grid. This can be improved by using a governing mechanism to change the guide vanes enabling the mechanical power to follow the electrical power. When the mechanical power equals the electrical power, the generator speed is equal to synchronous speed and so the frequency is maintained to 1 pu.

3.2 Closed loop simulation with governing action

Different simulation cases have been studied to understand the closed loop response of the VSHP plant when the governor is actively controlling the guide vane openings. Load changes were introduced as external disturbances acting on the system in different ways as stated below. The power control by VSG allows the power injected to the the grid to follow the load change given as reference power exactly.

- Response when the load steps down after some time
- Response when the load steps up after some time
- Response when the load ramps up after certain time
- Response when the load ramps down after a certain time

3.2.1 Response for step change in load

- Response when the load steps down after some time:

The closed loop responses of a VSHP for step down load change are shown in figure 7. The load change is simulated by stepping down the load reference power (P_g^*) from 0.9034 pu to 0.8 pu after 30 sec.

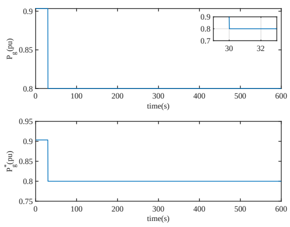

Figure (a)

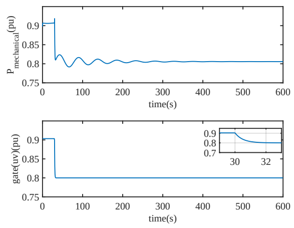

Figure (b)

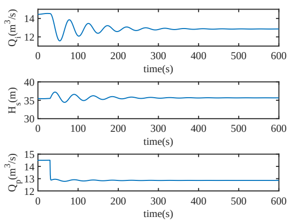

Figure (c)

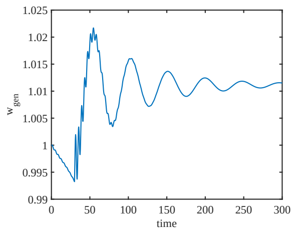

Figure (d)

Figure 7: VSHP response for stepdown load: (a) injected power, (b) mechanical power and guide vanes operation (c) hydraulic part, (d) generator frequency

- Response when the load steps up after some time: The closed loop responses of a VSHP for step up load change are shown in figure 8. The load change is simulated by stepping down the load reference power (P_g^*) from 0.9034 pu to 1 pu after 30 sec.

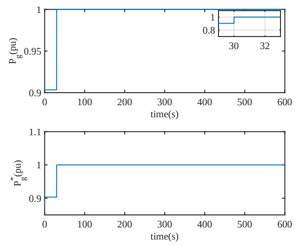

Figure (a)

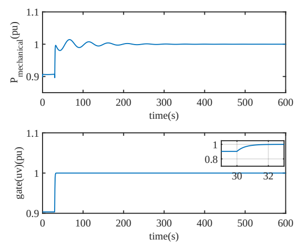

Figure (b)

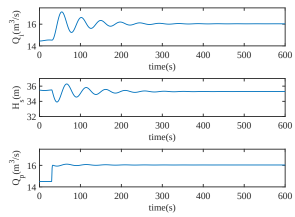

Figure (c)

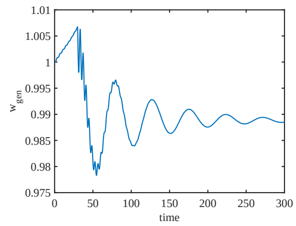

Figure (d)

Figure 8: VSHP response for stepup load: (a) injected power, (b) mechanical power and guide vanes operation (c) hydraulic part, (d) generator frequency

The step change in load leads to the operation of guide vanes in similar fashion, which leads to more sustained oscillations in the hydraulic part ad the mechanical power. This makes the generator take some time to settle down in steady state frequency, as seen in sub figure (d) of figures 7 and 8. However, this pattern in load change might be a little unrealistic when we work with actual load curves.

3.2.2 Response for ramping load

- Response when the load ramps down after certain time:
  The closed loop responses of a VSHP for ramping down load are shown in figure 9. The load change is simulated by ramping down the load reference power (P_g^*) from 0.9034 pu to 0.8 pu starting from 30 sec to 120 sec.

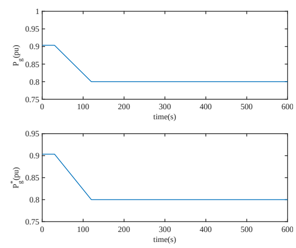

Figure (a)

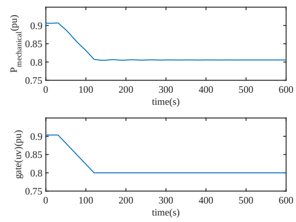

Figure (b)

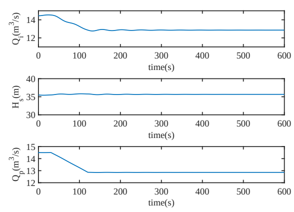

Figure (c)

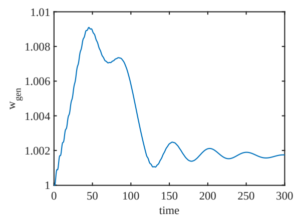

Figure (d)

Figure 9: VSHP response for ramping down load: (a) injected power, (b) mechanical power and guide vanes operation (c) hydraulic part, (d) generator frequency

- Response when the load ramps up after a certain time:
  The closed loop responses of a VSHP for ramping up load are shown in figure 10. The load change is simulated by ramping up the load reference power (P_g^*) from 0.9034 pu to 1 pu starting from 30 sec to 120 sec.

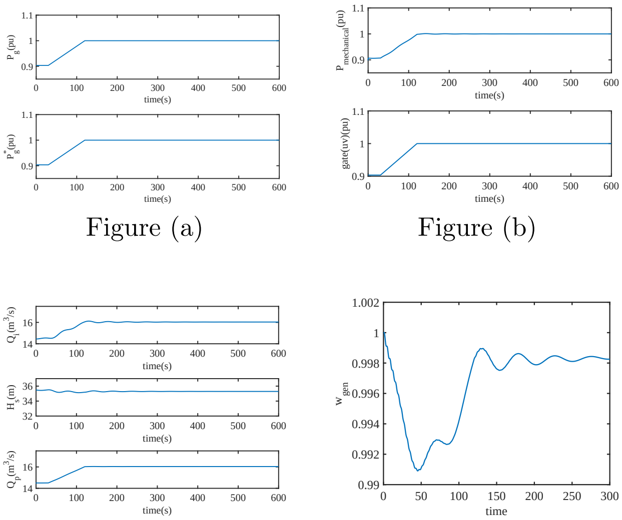

Figure 10: VSHP response for ramping up load: (a) injected power, (b) mechanical power and guide vanes operation (c) hydraulic part, (d) generator frequency

It is seen from the figures 7 and 9 and also from figures 8 and 10 that the ramp change in load is better followed by the VSHP as compared to the sudden step change. In addition to this, the turbine mechanical power oscillations and upstream variables' oscillations are smaller in case of ramp load change as compared to step change.This suggests that both the flow and pressure in the water ways are less oscillatory when the electrical power load is changed gently (ramped up) than for a sudden step change. For the safety of the mechanical components, lower oscillations in the flow and pressure are desirable. Furthermore, the frequency deviation after the governor has controlled the gate is also lesser in case of ramp load change compared to step load change as seen in sub-figure (d) of 7 and 9 for decrease in load and in sub-figure (d) of 8 and 10 for increase in load. This is because the actual load change pattern experienced by hydro power resembles better with the continuously changing ramp pattern rather than the sudden step change. This can be justified better by looking at actual load curves of any power system (Kabeyi and Olanrewaju (2023)).

With a change in injected power, the output power from the synchronous generator changes. This changes the turbine-generator speed because of imbalance in mechanical and electrical power. Then, the governor action (PI control for this paper) tries to reduce this deviation in speed by controlling the water flow into the turbine to reduce this power imbalance so as to maintain the synchronous speed of turbine-generator.

However, because of the large time constants of governor and hydraulic systems, the mechanical power cannot change instantaneously and undergoes some oscillations for a while, deviating the turbine-generator speed away from the reference speed for a short time. In case of VSHP, the grid side is decoupled from the turbine and synchronous generator because of presence of VSG, and so the grid frequency remains undisturbed during this turbine-generator speed deviation.The decoupling is achieved due to the presence of converter. Though these mechanical power oscillations and frequency deviations are isolated from the power grid, they still have effect on the hydropower system.

With the governing action, the upstream hydraulic variables like penstock flow, surge tank head and inlet pipe flow changes. The guide vane operation must be slow enough to maintain the upstream hydraulic variations within limits.

Since the turbine speed is allowed to deviate temporarily from its reference value, the size of step change of injected power by VSHP is limited by the limits in upstream hydraulic variables.With larger step change in reference power, larger opening or closing of guide vanes causes mechanical power to undergo larger oscillations. This might lead to bigger mass oscillations on the hydraulic side and also might lead to huge pressure imbalances. For a load drop from 0.9 pu to 0.1 pu, the upstream oscillations are shown in 11. This figure clearly shows the negative flow in inlet race and huge oscillations in surge tank level causing it to overflow.

In these situations, just the governor control using PI might not be enough. So, a control system should be designed to enable the smooth transition and prevent large oscillation of all the variables involved. The control system should be able to address multiple objectives which can include upstream pressure control, reduction of oscillations in flow and mechanical power, maintaining maximum turbine efficiency, and even grid support. This multi-objective control can be designed using more complex control scheme like the model predictive control or other forms of optimal controller. Also, the hydropower or grid undergoes some unanticipated state or load changes during operation, so the designed control system must preferably be able to handle these uncertainties as well. Stochastic optimal

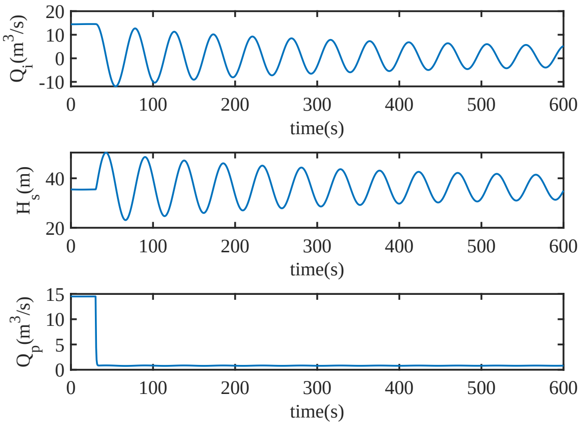

Figure 11: Response in hydraulic part for large step change in load

control methods can be designed for this case.

4 Conclusion

A complete time domain model of VSHP including the hydraulic part and virtual synchronous generator along with the simplified grid model is presented in this paper.The model shows active power control of VSHP and the stabilization of electrical frequency. It is simulated for step and ramp load changes in the grid side to study about the hydraulic and electric transients behaviour. Also, the anciliary services that a VSHP can provide to the grid is also taken into account.

It is found that the power reference from the grid undergoing sudden load changes is exactly followed by the VSHP maintaining a frequency balance in the grid. Also, for small load changes and reference power within the limits, the VSHP has smooth operation even in the hydraulic dynamics like flow and pressure along the water way.Furthermore, ramp load change led to more smooth operation as compared to step load change. Some oscillation in the upstream hydraulic dynamics were seen for sometime after the load change but these oscillations were within the limits for small step load change. However, if the load changes in larger steps, or if unanticipated power imbalance occurs, or any other type of disturbance occurs in the grid, proper control strategy is required to operate the VSHP in desired manner.

In addition to this, the model can be refined by addition of excitation system and voltage loops of converter to look at the voltage and reactive power support capability of VSHP.

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Appendix

Initial conditions for VSHP

Q_i = 14.4488 m/s
H_s = 35.4834 m
Q_P = 14.4488 m/s
u_v = 0.9
P_{dist} = 0 pu
P_g^* = 0.9034 pu

Values of parameters

1. Reservoir
   h_R = 20m
2. Inlet Pipe
   D_i = 4 m L_i = 1000 m
   H_i = 25 m $\rho = 1000\ kg/m^3$
   P_{atm} = 100 KPa
   f = 0.05
   $g = 9.8\ m/s^2$
3. Surge tank
   D_s = 3m f = 0.05
   l_s = 40m
4. Penstock
   H_p = 70 m L_P = 80 m
   D_P = 3 m f = 0.05
   C_v = 5
5. Turbine R_1 = 0.4952 m
   R_2 = 0.59637 m
   β_2 = 2.8362 radians
   β_1 = 1.7308 radians
   w_1 = 0.4195 m
   k_1 = 1

   Nominal values for turbine design
   Nominal flow rate in penstock = 14.4488 m/s
   Nominal head = 100 m
   nominal grid frequency = 50 Hz
   calculated $\alpha_{nominal}$ = 0.349 radians
   Mechanical power base value = 1.4 Mw
6. Synchronous generator
   H= 6.5
   D = 0
7. VSG and Grid
   $K_{VSG,P}$ = -100
   $K_{VSG,D}$ = -33.6
   H_g = 25.35
   D_m = 0.2 pu
   S_n = 1 pu
   w_{ref} = 1 pu
   $basefrequency$ = 50 Hz