Modelling and Optimisation of Deviation in Hydro Power Production

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Abstract

In 2009 a new price system for the produced power was introduced for Norwegian hydro power plants. Basically a power producer gets punished if his production deviates from the scheduled production. The power plant is paid for the actual production: if too much power is produced that the price for the excess power is low. Even worse if too little power is produced the power plant has to pay a fine.
If such deviation occurs it is very important to identify components/systems that are responsible in order to adjust the controller or replace the faulty equipment. This paper describes the first step in problem solving, by presenting the development of a model of a hydro power plant that shows differing power production. The modelling part was done in Modelica® using the `HydroPlant Library`[1] of Modelon AB. The model was parametrised using construction data and validated using data from test and operation runs.

Keywords: Modelica, Hydro Power Systems, HydroPlant Library, Test and Validation

1 Introduction

Several things affect the actual production in the power plant. The turbine governor controls guide vanes in the drum case, which in turn determines the power production. The most important input is the set-point. In addition it is possible to vary how sensitive the controller is wrt. changes in the frequency (also known as *droop control*). The droop is set by the national grid company, *Statnett* in case of Norway.
The produced power also varies with the water level in the reservoir. With a fixed guide vane opening the produced power increases when the reservoir level increases and decreases when the level decreases. The reservoir level is also fed to the turbine controller as an input and the controller should in principle compensate varying levels automatically.
In general, the various measurements, other inputs, and transformed signals used as inputs to the turbine controller, can contain uncertainties which may lead to production deviation.
In the past it occurred that a power plant called "Sundsbarm" which is located in Seljord, Norway has experienced a certain power production deviation. In order to investigate the reason for this deviation a reference model using the Modelica modelling language was developed and validated. With the help of this model ideally the reason for production deviation could be identified.

2 Main Components of a Hydro Power System

Hydropower facilities regarding if they store water for peak load period or not, and the way they store the water, can be classified into several categories:

Storage Regulation (Impoundment) This is the most common development of hydroelectric power plants in which a dam is used to store a large quantity of water in a big reservoir. Potential energy of the stored water then can be released in a controlled way.

Diversion Part of the river water is diverted into a canal or a tunnel and is passed through the power station and then might join the river again in the downstream. This development can use the natural difference in height of the river at the upstream

[1] For more information on this library see: `https://modelica.org/libraries/HydroPlant`

and downstream locations and may not require a dam.

Run of River In the run-of-river type, a small dam with little impoundment of water is used. Short tunnels (called penstocks) direct water to the power station using the natural flow of the river. Capacity of generating electricity in a diversion or a run-of-river station is dependent on the amount of water flowing in the river.

Pump Storage In pump storage development water is pumped to a higher reservoir during periods of low energy demand. The water is then run down through the turbines to produce power to meet peak demands.

Hydropower stations may also be classified by the type of their loads into Base-Load and Peak-Load plants [1]. The main focus of this paper will be on the Storage Regulation (Impoundment) type of hydropower stations.

2.1 The Water Way

Figure 1 shows an example cross-section of an impoundment hydropower station. The water passage starts from the upstream reservoir and ends at the downstream pond/river. The difference of elevation between water surfaces in the reservoir and the downstream pond determines the total head (gross head) of the water in the system. Because of the energy loss in the water passages due to friction, the effective head of the water that can be exploited is less than the total head.
Different parts of the water passages in this type of power plant are described briefly.

Intake Intake is the inlet of the head race tunnel which is equipped with Trash Rack for preventing big solid objects from entering the tunnel and Gate Door for isolating the tunnel for maintenance.

Head Race Tunnel or Conduit Head race tunnel (conduit) connects the reservoir to the penstock near the power house. It can be equipped with sand traps for collecting sand and garbage that had passed through the trash rack in the intake. The tunnel can be as long as 45 km like in "Muela" power station in South Africa [2]. It is also possible that the tunnel have inlet branches from more than one reservoir.

Surge Tank/ Surge Shaft Surge tanks or surge shafts might be used in different parts of the water passage to prevent the "water hammer" effect. When the water flowing in tunnels or pipes is accelerated or decelerated, pressure surges are created in the waterway which their magnitude may be much larger than the nominal pressure in the waterway. This effect is known as "water hammer". The strength of the pressure surges depends on the value of acceleration/deceleration and the length of the waterway. The waterway shall be built strong enough to withstand these pressure surges (often not an economical solution) or the surge magnitude shall be limited/ controlled somehow. One way for reducing the surge amplitudes is using surge shaft/ surge tank. Some other means of controlling the water hammer are:

- Limiting the gate or valve closure time
- Using pressure regulator valves / relief valves located near the turbine

Penstock A penstock (also called Pressure Shaft) is a pipe made of concrete, steel, fiberglass, or wood that is used to carry water from the supply sources to the turbine. This conveyance is usually from a canal or reservoir or from a tunnel. Penstocks may be equipped with shut-off/isolation valves. The control valve (e.g., guide vanes) at the turbine side regulates the water flow through the turbine.

Turbine Case The turbine case is the final component of the water passage before the guide vanes and the turbine runner. Here turbine cases for Francis turbine will be described shortly.

Guide Vanes Guide vanes are located between the turbine case and the runner of Francis turbines. These are movable vanes that are actuated by turbine governor to control the flow rate of water through the turbine and hence controlling the load of the turbine.

Turbine Runner Turbine runner for a Francis turbine is a reaction type turbine. Instead of using a water jet (like for impulse type turbines like Pelton turbines) a water flow is allowed to pass through the runner.

Draft Tube Draft tubes are the final components of the water passages of hydropower plants with Francis and Kaplan Turbines. Draft tubes carry away the water from turbine to the downstream channel or pond (the tail race).

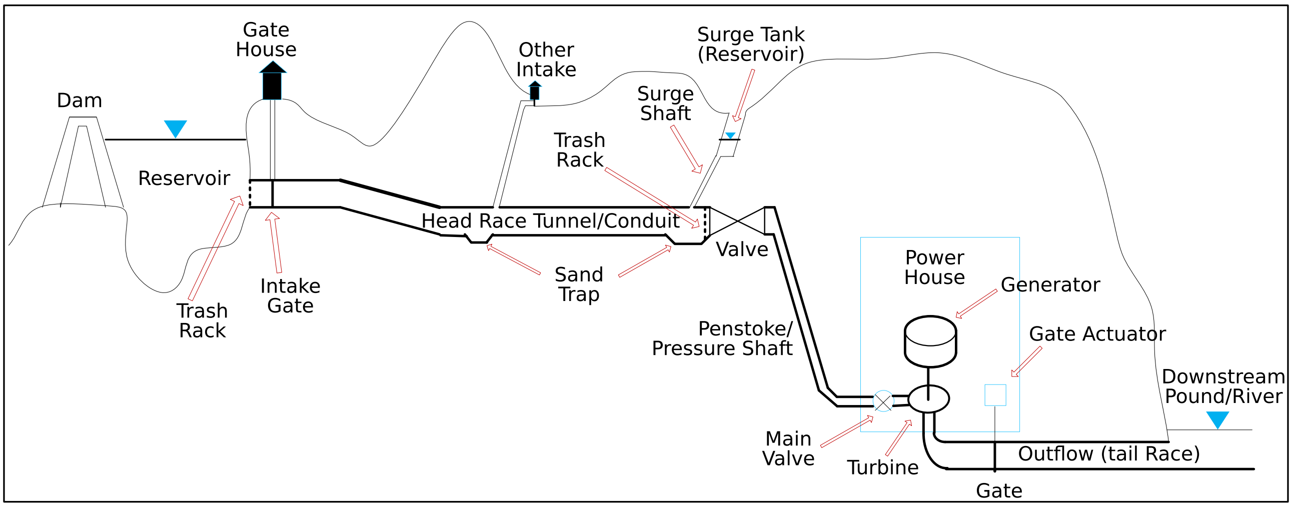

Figure 1: Example Schematic Diagram of an Impoundment Hydroelectric Station

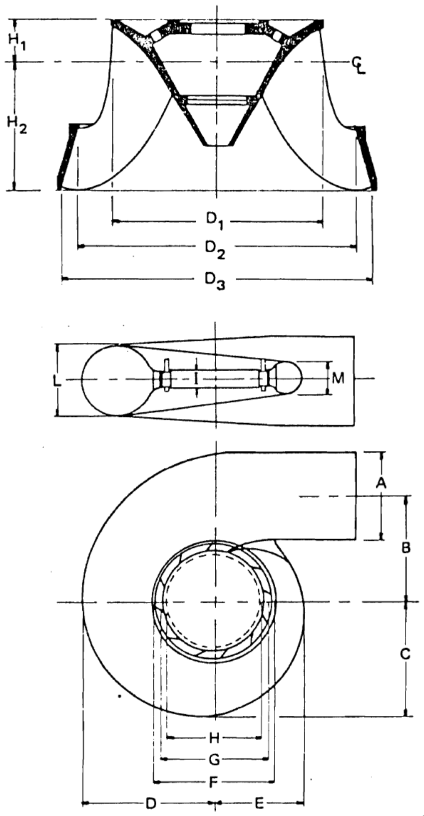

Figure 2: Francis Turbine Case with Dimensions [1]

Usually spiral cases are used for delivering water to the Francis turbine. Figure 2 shows a typical Francis turbine and its case. In general, following considerations shall be taken in design of the shape and dimensions of the case and runner:

1. The cross-sectional area of the spiral case must decrease so that the turbine runner is supplied with water uniformly around its circumference.

2. Irrationality of the flow inside the case shall be maintained.

2.2 The Electrical System

It follows a very brief introduction into the generator theory.
The generator converts the mechanical energy from the turbine into electric energy. The basic principle behind a generator was discovered by Michael Faraday, that a voltage is induced in a conductor when it moves through a magnetic field. Faraday's law of electromagnetic induction is explained in equation (1):

$$emf = -N\frac{\mathrm{d}\phi_B}{\mathrm{d}t} \tag{1}$$

Where

$$\begin{aligned} emf &= \text{electromotive force [V]} \\ \phi_B &= \text{magnetic flux [Vs]} \\ N &= \text{number of wires in the conductor} \end{aligned}$$

The Generator has two main parts: The rotor, which is the rotating part, and the stator, which is the stationary part. The rotor is delivering the magnetic field, and the copper coils in the stator get an induced voltage from the rotating magnetic field. There are two main types of generators, synchronous generators and asynchronous generators. The synchronous generator is the most used generator in bigger hydro power plants. Smaller hydro power plants may have asynchronous generators, such as smaller hydro power plants which produce up to about 5 MW.

2.2.1 Synchronous generator

The synchronous generator has a DC electric field in the rotor. In reality, a reverted synchronous AC generator (with armature windings on its rotor) connected at the end of the synchronous generator shaft produces this DC current. A principal sketch of a two-pole, single-phase synchronous generator is shown in Fig. 3. It shows the field conductors in the rotor which makes the magnetic field, and the stator conductor which gets an induced voltage from the rotating magnetic field. When the rotor turns and the poles change place, the induced voltage in the stator is alternated. This makes the generator produce AC (Alternating Current) voltage from the DC current in the rotor. The terminal voltage of the generator can be controlled by the magnetising current in the rotor.

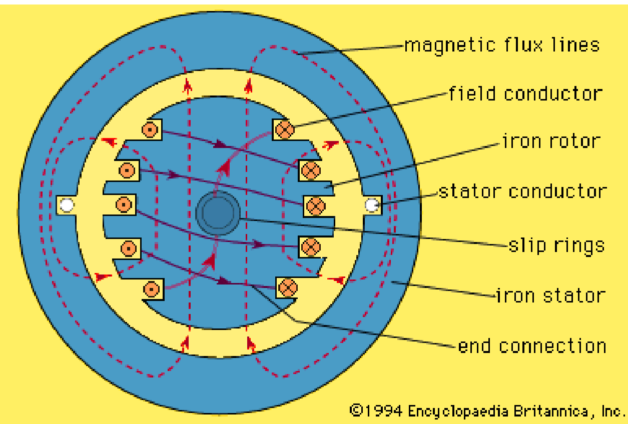

Figure 3: A 2-pole single phase synch. generator [3]

2.2.2 Power factor

The power factor is a very important subject when it comes to electric power. When the voltage and current are in phase (no lag) then the power factor is maximum, i.e., 1. This gives the optimal power output. The definition of power factor is:

$$PF = \frac{P}{S} = \cos\varphi \qquad (2)$$

Where

$S =$ apparent power [VA]
$P =$ active power [W]

2.3 Control System

2.3.1 Turbine governor

The turbine governor's main task is to control the power output and the rotational speed of the turbine and also to smooth out differences between generated and consumed power at any grid load and prevailing conditions in the water conduit [4]. At the same time the governor also need to close down the admission at load rejections or when a need for an emergency stop rises. This has to be done in accordance with specified limits of rotational speed and pressure rises in the waterway.

Deviation between power generation and consumption in the grid will cause an acceleration or deceleration of the rotating masses of generating units. Acceleration happens in case when generation is more than consumption. The turbine governor then will cause a deceleration of the water flow. At the same time pressure in the penstock will increase.

In order to keep the rotational speed within specified limits at load rejections the admission – closing rate must be equal to or higher than a given value [4]. In the opposite way the closing rate of the admission have to be equal or lower than a certain value in order to keep the pressure rise in the conduit within specified limits.

The turbine governor acts in two modes: speed control and load control. Speed control mode takes place when the generator is isolated from the grid (MCB is open). In this mode the governor regulates the speed of the turbine-generator with the speed set point. Load control mode takes place when the MCB is closed. In this mode the governor regulates the generated power with the load set point and through a mechanism called "droop" which is described in section 2.3.2. The governor output signal in a Francis turbine power generation unit is applied to the guide vane servomechanism and hence the governor controls the unit through the guide vane position.

2.3.2 Speed Droop Control

In case of frequency increase (decrease) in the grid, each power generation unit reduces (adds) a fix percentage of its total rating output power multiplied by the amount of the change in the grid frequency' from (to) its output power. The amount of this power can be calculated from equation (3):

$$S = \frac{\Delta f / f_N}{\Delta P / P_N} \cdot 100\% \qquad (3)$$

Where

$$S = \quad \text{permanent speed droop [\%]}$$
$$f_N = \quad \text{nominal frequency [Hz]}$$
$$P_N = \quad \text{nominal power [MW]}$$

Where the permanent speed droop in equation (3) is a percentage number which is decided by the grid administration (e.g., Statnett in Norway). For example in Norway for a stable operation of the electrical grid the permanent speed droop is currently set to 10% .

2.3.3 Power/Frequency Control

In every electrical system the power needs to be produced when it is consumed. It is not possible to store electrical energy. Energy has to be stored in the form of reservoirs for larger power systems, and as chemical energy (batteries) for small power systems. This means that the production system must be sufficiently flexible to both changes in consumption and the outcome of the production, and that the transfer can be handled instantaneously, preferably without consumers noticing it. For example, the national grids in Norway, Sweden, Finland, and at Sjælland in Denmark are all connected to one coordinated synchronous grid. This means that events in one of the sub-grids can affect the other grids in the other countries.

The frequency is a measure of how fast the machines in the system rotate. If it becomes an increase in load (as with any other rotating machines) the frequency (speed) will decrease, and at load rejection the frequency will rise. The controlling devices will automatically perform a primary control so that it again is a balance between production and consumption. How much the speed decreases are influenced both by the total torque, and by how quickly the primary control is done.

At frequencies below 50 Hz, the total load will get higher than the desired production and at frequencies above 50 Hz, total load will become lower. In practice, the load varies continuously. Consequently, the controlling devices continuously need to perform the frequency control.

The power/frequency control is normally exacted in two stages.

1. Primary control or primary frequency control is simply the application of the speed droop control as mentioned in section 2.3.2. This kind of control is applied automatically and is built into all turbine governors. This means that when the frequency deviates from the optimal 50 Hz the turbine governor will increase or reduce the guide vane opening according to the droop control settings.

2. After the primary control has settled we will still have a constant frequency deviation. This is when the secondary control is used to compensate the deviation with the help of the *Load Frequency Control* (LFC). The LFC will simply raise or lower the set-point so that frequency is corrected again.

   LFC is normally used in combination with *Automatic Generation Control* (AGC) where different generation regions are taken into account in order to balance the power production [5]. However internationally there exist different interpretations and implementation of the Automatic Generation Control.

First the primary frequency control is applied.

3 Complete Dynamic Model

This section discusses the basic hydraulic theory related to hydropower plants, hydro power modelling in the Modelica `HydroPlant Library` (HPL), analytical models for hydropower plant's hydro dynamics and analysis. The total system is divided into several subsystems, namely reservoir, conduit, surge tank, penstock, turbine, generator, and grid. The `HydroPlant Library` uses digitised turbine characteristics (in practise turbine characteristic is given as a chart so called "Hill Charts" by the manufactures) and this may lead to some uncertain results (because some extrapolations and interpolation needed among data points). So emphasis is put on having a good analytic model for turbine. An analytical model for a Francis turbine is proposed in [6].

In the `HydroPlant Library` some units (e.g., conduit, penstock) are divided into sub volumes also called control volumes (CV) and each sub volume is characterised by temperature and pressure (so called the state of a control volume). Two Ordinary Differential Equations (ODEs) are derived from the conservation equations (i.e., mass, energy). Mass flow rate between two adjacent control volumes is governed by a third ODE which is derived using the momentum conservation. The main assumption is that state is uniformly distributed throughout the CV. This is the so-called "Lumped Parameter" assumption.

Two dynamic equations will be derived for temperature and pressure. But however more concern is given into deriving equation in Laplace or frequency domain which will help to study the dynamics of the systems. A detailed discussion is given in [6]. When a hydropower plant is modelled (in Modelica), local resistances (e.g., trash rack losses, bend losses) are considered to be *minor* pressure losses while the *major* losses are due to wall friction. So in the Modelica model those minors losses are neglected, only major wall frictional losses considered (`HydroPlant Library` blocks take care of this).

4 The Sundsbarm Hydro Power Plant

In this section only some parts of Sundsbarm Hydro Power Plant are explained.

Francis Turbine governor The turbine governor at Sundsbarm is a TC 200 digital turbine governor from Kværner. It is a PID controller, and it has inputs for frequency reference (f_0) and frequency measured out from the generator (f), as well as inputs for load reference (P_0) and power measurement after the generator (P).
The set point for frequency and the permanent speed droop are controlled and set by the operator or a overall control system.
The functions inside the governor at Sundsbarm and the function of the governor used in the `HydroPlant Library` are not identical. In order to obtain as similar control of the power plant inside Modelica and the real process at Sundsbarm these functions need to equal each other. In order to get this similar to each other we have looked into the block drawings and made a simplified block drawing of the functions inside the TC 200 governor at Sundsbarm. We then compared this with the block drawing from the `HydroPlant Library` and we obtained the controller in Fig. 4.

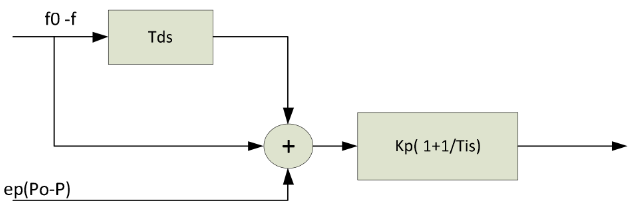

Figure 4: Simplified block-drawing from the turbine governor at Sundsbarm

This structure can be reorganised to the controller shown in Fig. 5.

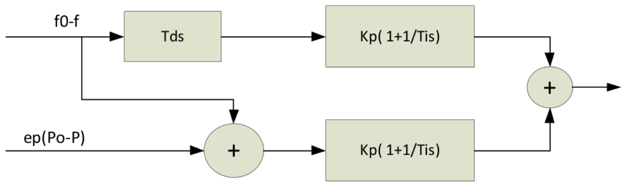

Figure 5: An equivalent controller block diagram to the one at Sundsbarm

This gives two governors:

- One with PI characteristic
- One with PD characteristic

Turbine The turbine placed at Sundsbarm is a vertical Francis Turbine with a performance of 104.4 MW, and is constructed for a nominal head (H_{nom}) of $460\,m$. The efficiency and volume flow of the turbine is calculated in the Modelica model using a look-up table.

Generator and Main Circuit Breaker In Sundsbarm there is one generator delivered by "National Industri" Drammen, Norway. The nominal performance is $118\,MVA$ and the nominal frequency is $50\,Hz$. The number of generator poles is 12. Inertia momentum of the generator is given by Alstom and is equal to $850,000\,Kg.m^2$.

Reservoir The reservoir type for the Sundsbarm plant is an impoundment dam. This means that the water source has a water storage that makes it possible to store energy in the reservoir. The lake *Sundsbarmsvatn* is used as a reservoir. Other lakes are connected to *Sundsbarmsvatn*, to lead more water through the power plant. The other lakes are not modelled, because they are not connected directly to the conduit channel or to the penstock.
The Sundsbarm lake is approximately $12.5\,km$ long and $0.75\,km$ wide. These approximate sizes of the reservoir are used in the model, because normal operation conditions are of interest, not the level of water varying over a long period in *Sundsbarmsvatn*.

Conduit channel The conduit channel consists of the intake at the reservoir, *Sundsbarmsvatn*, a trash rack, and an intake gate. Just before the penstock there is another trash rack, a surge shaft and an emergency valve. There is an additional small intake called *Finndalsåi* that is connected directly to the conduit channel but was not included in the model.

Penstock The penstock for Sundsbarm hydro power plant consists of a steel pipe inside a tunnel. The penstock is 600 meters long and is tilted 45°. The start of the penstock is at $541.5\,m$ above sea level and the end of the penstock is at $112.5\,m$ above sea level. Diameter of the penstock is about 3 meters.

Surge shaft The surge shaft for Sundsbarm hydro power plant is a pipe or tunnel with a length L of about $138\,m$ which is tilted by 67.5°.

Outflow tunnel The outflow tunnel consists of a rough tunnel that goes from the draft tube at the turbine and to the output reservoir. The outlet tunnel has its lowest elevation closest to the draft tube at $107.5\,m$. At the end of the tunnel the elevation is $4.5\,m$ higher, at $112\,m$ above sea level.

Reservoir at outlet The reservoir at the outlet is the river in *Seljord*. The reservoir model used here is also the `Fixed_HT` model together with a model of the reservoir. The Fixed HT model has an infinite volume with prescribed water height and temperature. The level at the outlet reservoir is $123\,m$ above sea level.

4.1 Modelica Model of Sundsbarm Power Plant

Putting all the different parts together using the components from the `HydroPlant Library` and filling in their respective parameters we gain the complete dynamic model as shown in Fig. 6.

5 Test & Results

5.1 Validation of the Model

5.1.1 Consistency of Turbine Parameters

The first attempt in validating the model is to compare the turbine response with the performance test results which are included in measurements done back in 1993 [7]. This is done to ensure that the parameters entered into the turbine model (e.g., nominal power, flow rate, Mechanical efficiency) are consistent with the turbine data table values.

For validating the consistency of the turbine model a simple model as shown in Fig. 7 was created.

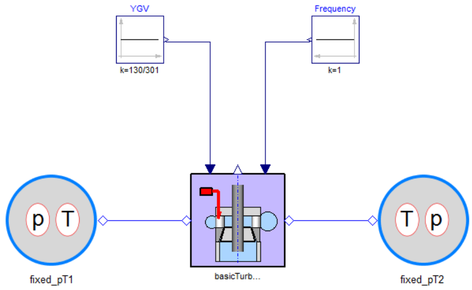

Figure 7: Model for simulation of the turbine consistency

This model is simulated for different guide vane openings given by the measurements from 1993 [7]. The frequency is kept equal to the nominal value in all of the simulations. In each simulation the constant pressure drop across the turbine is set to be equal to the value corresponding to the relevant guide vane opening.

5.1.2 Step Response Simulations

For this simulation the model shown in the Fig. 8 is used in which the input command is directly applied to the guide vane.

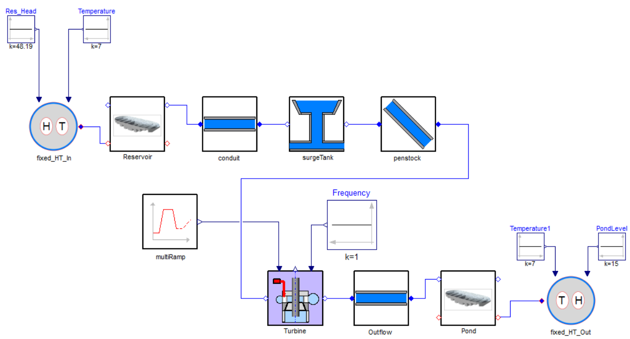

Figure 8: Test model for applying step changes in the guide vane input

Fig. 9 shows the step response of the model for a positive step change at time $t = 500\,sec$ and then a negative step change applied at $t = 1500\,sec$. For this simulation the relative pipe roughness of the conduit and the outflow tunnel is set to 0.065 as found from calculations. The relative pipe roughness of the penstock is set to 0.003. The guide vane servomotor opening time is limited to $20\,sec$ (full range opening) and its closing

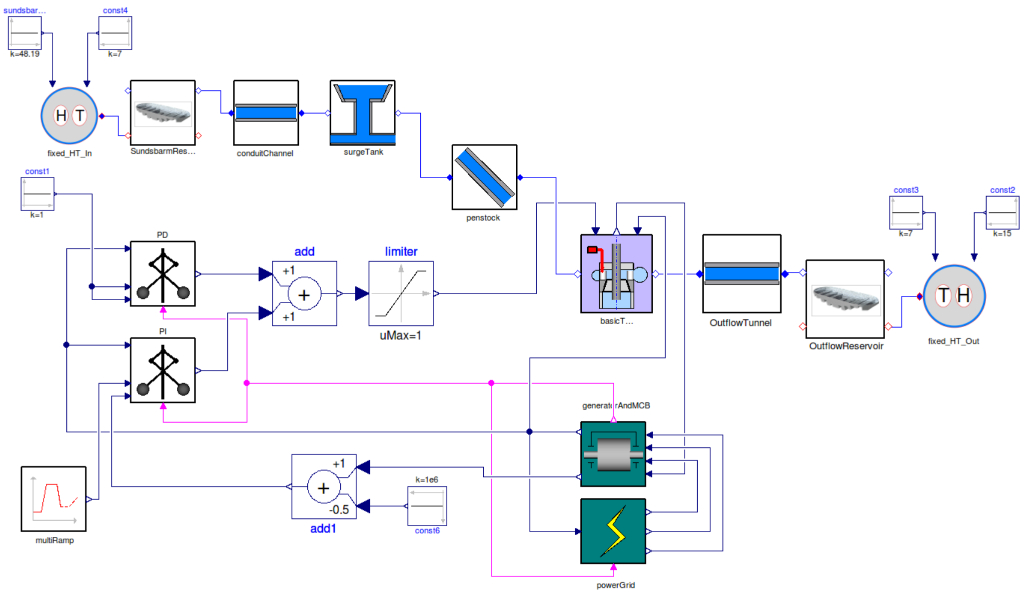

Figure 6: Complete model of Sundsbarm Power Plant modelled using the `HydroPlant Library`

time is limited to 2.5 *sec*. This effect can be seen in the guide vane opening in the Fig. 9. Because of this difference, the magnitude of the surge pressure at the turbine inlet is greater when the guide vane closes although the magnitude of negative change in guide vane opening is smaller.

5.2 Linearisation of the Model

Dymola can linearise nonlinear models around their steady state operating point. In this section a linear model will be obtained for the hydropower model that can be further analysed and used for design in the MATLAB environment. For this reason the model in Dymola needs some adjustments. Fig. 10 shows the resulting model.
After loading the steady state condition of the model in Dymola, a random noise input is used for linearising the model. The reduced order of the linearised state space model is 58.

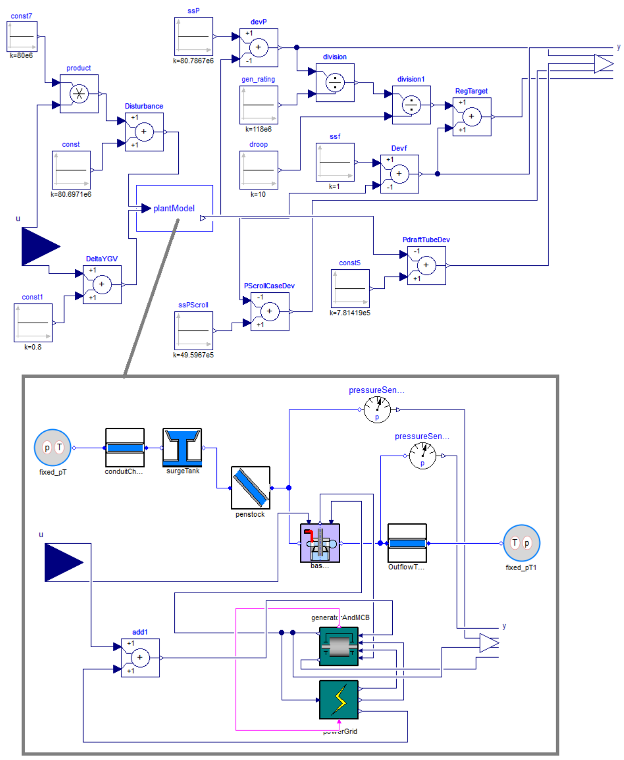

Figure 10: Adjustments done to the model before linearisation

5.2.1 Applications of the Linearised Model

The linearised model can be used for implementing more advanced control methods like the ones described in [8]. The model shown in Fig. 10 is specially taylored to be used for such control schemes:

- For saving number of state variables just fixed sources are used to model reservoires.
- For having a time invariant dynamics, the load in the grid block is set to be constant and then the changes in the grid is modeled merely by adding a random disturbance signal to the grid balance.

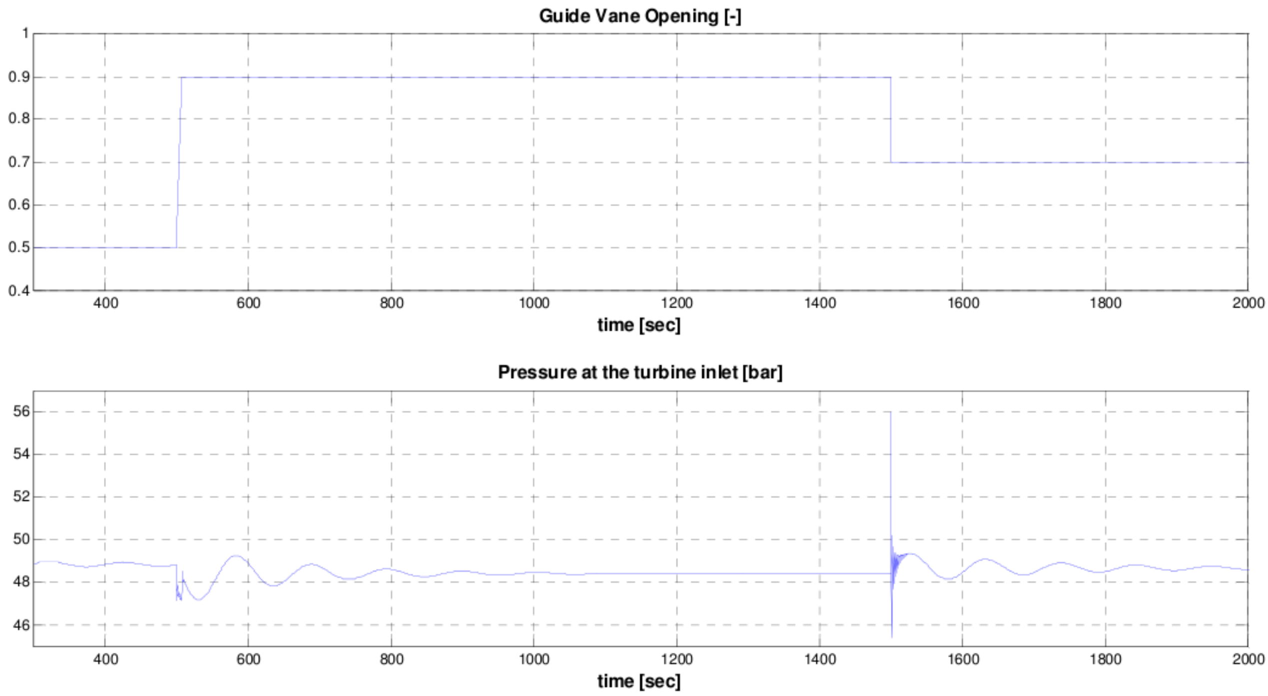

Figure 9: Step response (Relative pipe roughness of conduit and outflow tunnel=0.065 and Relative pipe roughness of penstock=0.003)

- The same opening and closing rate limites are considered for guide vane operation for better linearity. Additional rate for guide vane opening may be implemented in the controller.

- For having a strict constraint on the power generation/grid frequency values (to satisfy droop requirements) a combination of these variables are selected as output of the model and this combination can be used as a feedback for the controller.

- Other quantities (like pressure in different locations) can be selected as additional outputs to enforce constraints on the system state variables by controller. These constraints can be applied by advanced methods like Model Predictive Control. This can be considered as a future work.

6 Conclusions

In this paper the theory of hydro power systems was briefly presented. Based on dimensions and specifications, as well as structure drawings, (from Skagerak Energy's archive) a dynamic model of the Sundsbarm power station was created using the `HydroPlant Library` of Modelon AB.

At the time of writing only operational data of the power station were available. Therefore the model was tested against friction values from pressure measurements at the conduit channel. Obviously with the more data points, a better model can be obtained. The data available do not cover the complete operational range of the guide van opening and the flow rate of the turbine. The relative wall roughness for the conduit was calculated from the measurement data. The model was then tested with the calculated roughness to verify that the same friction loss can be reproduced and the result was comparable. This means that steady state calculations in the `HydroPlant Library` are reliable.

Finally suggestion was made for implementation of a model predictive controller as part of a future work. A linear model had to be made in order to develop a MPC. The linear model had additional outputs for pressure in penstock and draft tube. Therefore a MPC controller could have these output constraints for pressure in penstock and the draft tube, which is believed that gives safer and more optimised control of the Sundsbarm power plant.

Other improvements that could have been implemented for the plant is to have power feedback for the turbine governor at the grid connection, instead at the generator terminals. This means correcting the power set point with measurements at the delivery point of the power to the grid. This way the power production will have less deviation since the power readings for the grid operator are at the grid. This will allow the power plant to consider the loss of approx. 0.5 MW from the transformer, cables, and own power consumption, when adding a set-point for the plant.

7 Acknowledgements

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