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Abstract:

Water level in the pondage is an important parameter for a run-of-river hydraulic power plant. Keeping a reasonable high waterfall will help to reduce the total cost of power generation. The aim of the work for thesis is to study the control of the run-of-river power plant Grønvollfoss based on simulation model. The one-dimensional hydraulic model of Grønvollfoss power plant is developed based on the Saint-Venant equations. Saint-Venant equations is considered consisting of two partial differential equations which are continuity and momentum equations expressing conservation of mass and momentum. Based on the staggered computational grid, the Saint-Venant equation can be discretized into N sections, which shared the same hydraulic characteristics and interconnect with each other by inlet flow and outlet flow.

PI control algorithm is developed for the regulation of water level. The water level in response to different initial conditions has been simulated. The control system was tested under varying reference signal and disturbance. Detailed discussion about the result of these simulations has been carried out; it shows that the controller fulfilled the control objective.

The model is implemented and simulated in MATLAB.

Telemark University College accepts no responsibility for results and conclusions presented in this report.

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Preface

This project is carried out in the spring of 2013, and the report is the graduation thesis for my Master education in System and Control Engineering at Telemark University College. The work has been done with Skagerak Kraft as the external partner. Professor Bernt Lie has been the main supervisor and Ingvar Andreassen has been the main contact person from the external partner.

I would like to express my deepest and honest gratitude to my supervisor Prof. Bernt Lie for providing support and guidance to the thesis. I am thankful for his valuable comment and suggestions. My sincerely thanks also to Ingvar Andreassen for providing the information of the project and the visit to the power plant.

I would like to thank Telemark University College for providing the platform for the thesis work.

Finally, I would like to express my thanks to everyone I meet during my master study.

Porsgrunn, June 1st 2013

Yiyang Ruan

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1 Introduction

1.1 Overview

Norway is well endowed for developing its hydropower resources; the hydropower covers almost 100% of the total electricity production all over the country and the total volume of storage reservoirs for hydropower is close to 62 km³ (NVE and Ministry of Petroleum and Energy, 2003). Therefore, it is of interest to optimize the efficacy of the energy use by applying proper control strategy. For this purpose, a model of the power system is needed for the application of control strategy.

The basic principle of optimizing a run-of-river power plant is keeping the water level of the reservoir as high as possible. However, a too high level of water increases the risk of irregular flow of water to the power plants downstream, or even damage to the floodgates if blocks of ice flows over the top of the gate.

This thesis describes the use of floodgate to control the outflow of water, keeping the level of water at a desirable value. By manipulating the crane part of the gate raise or drop the blocking section to adjust the outflow of water, maintaining the desirable water level. The control strategy for controlling the outflow has been discussed in the report. The control strategy is based on controlling the opening percentage of the floodgate when the inflow rate is under variation. PI control algorithms have been used to control the water level.

The thesis focused on modeling and controlling of run-of-river power plant Grønvollfoss. The inlet flow of the plant is provided and disturbed by the upstream plant Årlifoss. The water level of the pondage should be controlled. The target is to keep a high and safety water level to maximize the power production.

1.2 Scope of Problem

The main objective of the thesis is to develop a sensible model of the dynamics of water level in the pondage of Grønvollfoss. Simulation of the model should be performed in MATLAB under different operating conditions. The model should also be tested with data from actual power plant. Moreover, the PI control strategy for controlling the water level has to be designed and simulated to satisfy the requirement of efficacy and safety. The attempt to develop a linearized model has been carried out. However, the simulation result of the linearized model cannot fully represent the behavior of the water level. Therefore, the implementation of model predictive controller (MPC) will not be presented in this report.

1.3 Current method

Current using model is based on the area of the pondage. The change of water level is calculated by inflow rate divided by the area. The whole pondage is considered to a entirety and the iteration of water has been neglected. This model is not accurate enough for the control requirement.

2 Overview of Run-of-river Power Plant

The objective of this chapter is to provide detailed information of run-of-river power plants along the river Tinnelva, especially focus on Grønvollfoss Power Plant. The chapter intended to explain the concept of power generation in a run-of-river power plant, as well as the information of reservoir and the dam.

2.1 Run-of-river Power Plant

Run-of-river power plant is a type of hydroelectric power plant that has either no, or small amount of water storage which is called pondage and utilizing the flow of a river for power generation. Unlike traditional hydroelectric power plant, run-of-river power plant uses natural river flow, while a conventional hydroelectric power plant stores significant amounts of water in the reservoir to generate power. Therefore, a large reservoir is not required for smaller-scale run-of-river power plant, which means the environmental impacts is minimal (Wikipedia, 2013b).

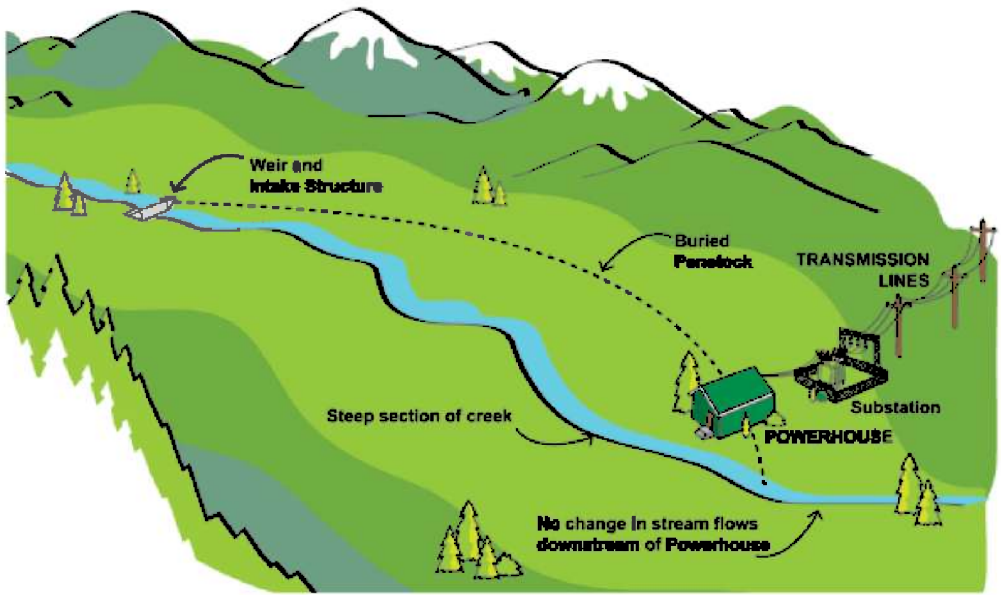


Figure 2-1: A typical run-of-river hydro power plant. (Image source: Hydromax Energy, Canada)

2.1.1 Diversion Reach

The section of the river between the penstock intake and the tailrace is the diversion reach (Kwagis Power, 2013). Part of the downstream water coming from the pondage part is

diverted through a pipe, which is called penstock, while the rest of water flows down naturally. The water through the penstock will then return to the river via a short tailrace after passing through the powerhouse and spin the blades of the turbine, see Figure 2-2.

2.2 Power Plants along river Tinnelva

Tinnelva is a river located east in the county of Telemark. The river flows from the lake Tinnssjøen and end at Heddalsvatnet. There are four power station along the river Tinnelva in total: Årlifoss, Grønvollfoss, Svelgfoss and Tinnfoss, see Figure 2-2. The combined installed capacity is 182 MW. Among them Årlifoss and Grønvollfoss are being operated by Skagerak Energi, while Svelgfoss and Tinnfoss are owned by Norsk Hydro ASA and Tinfos AS.

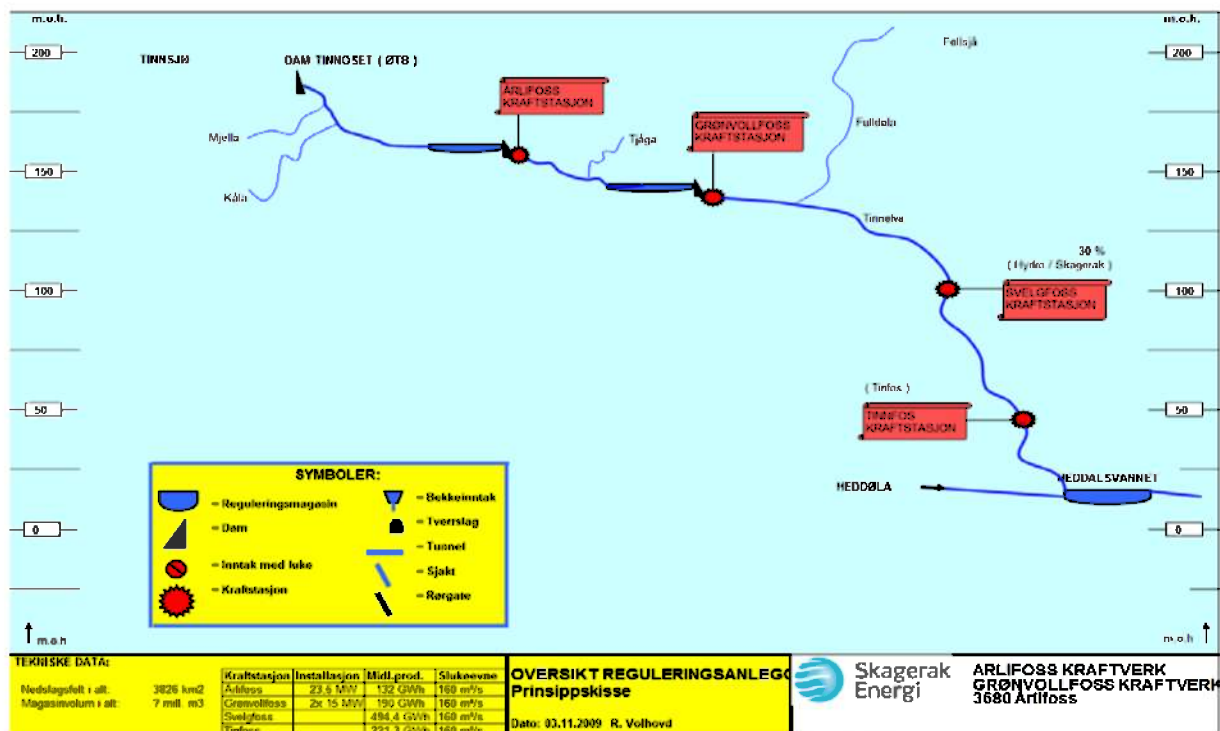


Figure 2-2: Run-of-river power plants located along Tinnelva. (Image source: Skagerak Energi, Norway).

In this thesis, I concentrate on Grønvollfoss Power Plant.

2.3 Grønvollfoss Power Plant

Grønvollfoss is a run-of-river hydroelectric power plant located in Skien watershed in Notodden municipality of Telemark running by Skagerak Energi. Utilizing the 22.6 meters waterfall height of Tinnelva River, the plant has an average annual production of 172 GWh with two Kaplan turbines installed (Ruan et al., 2013).

2.3.1 Kaplan Turbine

According to A.T.Sayers in the book “Hydraulic and compressible flow turbo machines”, the definition of turbine is:

“A machine that produces power by expanding a continuously following fluid to a lower pressure or head.”

A typical turbine consist of a rotating section with blades, the energy happen to transfer when the flow spinning the blades.

The turbine used in Grønvollfoss is of a type called Kaplan turbine. It is classified as axial flow turbine. The most significant characteristic of Kaplan turbine is its automatically adjusted blades, the degree of blades can be changed to achieve most efficacy according to the varying water head and load of unit. That is why a Kaplan turbine is also called “axial flow hydro turbine with movable blade” (Baidu Baike, 2013).

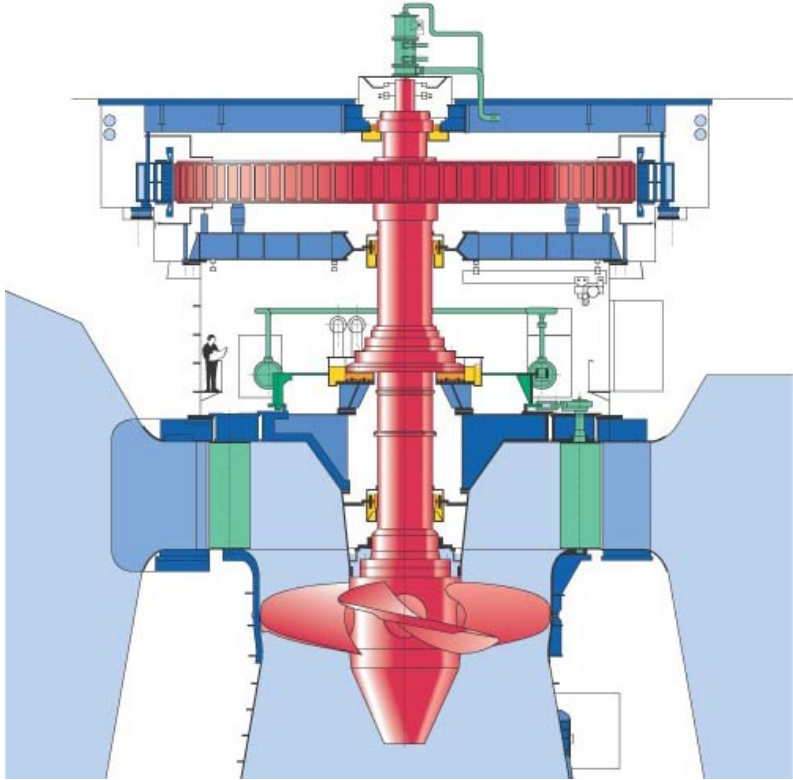


Figure 2-3: The front view of Kaplan turbine. (Image source: Voith-Siemens, Germany)

Water gives away its energy when passing through the turbine, spinning the propeller. The power production of Kaplan turbine can be calculated by following equation (Flaspöhler, 2007):

$$P = Q * H * \rho * g \tag{Equation 2-1}$$

Where,

- P The power production [W].
- Q The discharge of water [m^3/s].
- ρ The density of water [kg/m^3].
- g Gravity acceleration [m/s^2].
- H Water head [m].
-

When taking the efficiency in to consideration, the equation can be written as:

$$P = Q * H * \rho * g \quad \text{Equation 2-2}$$

Where,

η Efficiency [%].

2.4 Flooding

The Norwegian definition of flooding is different from English. The word *middelflom* (normal flood) is defined as the average of the highest daily average flow each year for a certain number of years (Wikipedia, 2013a). A river is considered to be flooding when the flow rate exceeds the middelflom value.

Norway has a varied landscape and therefore the reasons causing flooding differ from places to places. Main reasons can be:

- Heavy rainfall.
- Snowmelt.
- Melting of glaciers.

These phenomena can occur individually or in conjunction. Thus, large flooding often take place in summer.



Figure 2-4: Flooding in Grønvollfoss after several days' rainfall. (Photographer: Jan Erik Arud, Norway)

For Grønvollfoss, rainfall and snowmelt are the reasons causing flooding. By 21st of May 2013, several days of heavy rainfall resulted in a flooding of river Tinnelva. In addition, the lake Tinnsjøen, the source of Tinnelva, is full and there is a lot of snow in the mountain that has melted and flow into Tinnsjøen. This will amplify the flooding, and flow rate will be more than 600 cubic meters per second, see Figure 2-4. Thus, it is of interest to apply control strategy on the floodgate to prevent the damage of flooding.

2.5 Floodgate

A floodgate is a device designed to control the flow rate of water system. By adjusting the opening of the floodgate, the flow of water can be stopped completely or partly. There are three types of floodgates used in Grønvollfoss Power Plant; the capacities of them are listed in Table 2-1.

Table 2-1: The capacities of the gates in Grønvollfoss Power Plant. (Source: Skagerak Energi, Norway)

<i>Type</i>	<i>Capacity</i>	<i>Number</i>	<i>Capacity in total</i>
Segment gate	350 m^3/s	1	350 m^3/s
Roller gate	350 m^3/s	1	350 m^3/s
Spillway gate	150 m^3/s	1	150 m^3/s
Flood gate	90 m^3/s	9	810 m^3/s
Overall capacity		1660 m^3/s	

Segment gate or and roller gate are used as main control gate. It can be selected with a manual switch for which of these gates to be used. Normally, the floodgate in used of Grønvollfoss Power Plant is segment gate, while roller gate is essentially a reservation gate and other gates are not in use unless the power plant experiencing serious flooding. The segment gate is considered the simplest form of floodgate. It consists of a curved skin plate formed to a cylinder segment, supported by radial compressed arms which transfer the hydraulic forces to fixed bearings (Erbidti, 2004).



Figure 2-5: The segment gate of Grønvollfoss Power Plant.

The segment gate rotates about a horizontal axis, and the thrust from the water pressure will not act on opening or closing the gate due to its mechanical structure. The model of the segment gate will be discussed in Chapter 3.

3 Modeling and Simulation of the water level in run-of-river power plant

This chapter mainly describes the developing of dynamic hydro power plant model based on Saint-Venant equations and staggered computational grids. Simulation of the model has been conducted under different condition and the result has been discussed in the last section of this chapter. MATLAB has been used as the tool for modeling and simulation.

3.1 Introduction to the water level in Grønvollfoss Power Plant

As described in former chapter, Grønvollfoss Power Plant is the second plant along river Tinnelva, which means Grønvollfoss do not has a private regulation reservoir. It uses the outlet flow from uppermost plant Årlifoss, which is located in 5 km upstream from Grønvollfoss. Therefore, the water level must be controlled according to the inflow of the river.

Grønvollfoss has a highest regulated water level (HRV) at 144.50 meters above sea level. There is no specified minimum regulated water level (LRV). Water level in the dam must be in range of $HRV \pm 1$ cm. If Grønvollfoss Power Plant or any other plants along Tinnelva, running in an irregular condition, the deviation in water level is permitted. It will for example be desirable to utilize reservoir capacity Grønvollfoss to curb flow changes in the river at fault on the overhead power plants. This is to create the least problems for downstream power plants in the river.

At the level of 144.52 meters above sea level (2 cm above HRV), the water will flow over the dam. In winter, it is important to keep the water level below this level to avoid floating ice falling and damaging equipment and gates.

3.2 Saint-Venant Equations

For flow simulations, making use of the simplifications of Navier-Stokes equations are the most common way to develop a model. For shallow water like the pondage of Grønvollfoss Power Plant, one of the most accepted and used model is given by Saint-Venant equations.

3.2.1 Introduction to the Saint-Venant Equations

Saint-Venant equations (also known as the shallow water equations) are a 2-dimensional model that describes the water motion of flow under a pressure surface in a fluid. It consists of several partial differential equations based on Navier-Stokes equations. The case of Saint-Venant equations been used, the horizontal length of the water system is much greater than the vertical height, which allows the vertical dimension of the water motion can be removed from the equations by the hydrostatic pressure approximation, and the flow velocity is approximated by the depth-averaged flow velocity (van't Hof and Veldman, 2012).

The conservative form of Saint-Venant equations can be derived from equations of conservation of mass and momentum.

The mass equation (also called continuity equation) describes the mass balance of control volume, it represent that the rate of change of storage inside the volume is equal to the rate of change of flow with distance. The mass equation is:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q_L \quad \text{Equation 3-1}$$

The momentum equation describes the momentum balance of control volume, the equation is expressed by Newton's 2nd Law as the conservation of momentum of a control volume states that the net rate of momentum entering the volume (momentum flux) plus the sum of all external forces acting on the volume be equal to the rate of accumulation of momentum (Sánchez et al., 2010). The momentum equation is:

$$\frac{\partial Q}{\partial t} + \frac{\partial \left(\frac{Q^2}{A} \right)}{\partial x} + gA \frac{\partial Z}{\partial x} + g \frac{|Q|Q}{C^2 AR} = 0 \quad \text{Equation 3-2}$$

Where,

- Q inflow upstream [m^3/s];
- t time [s];
- x the spatial increment in the main flow direction [m];
- A the wetted cross sectional area [m^2];
- q_L the lateral inflow per unit length [$m^3/(s \cdot m)$];
- Z the water depth [m];
- g the gravitational acceleration [m/s^2];
- R the hydraulic radius [m];
- C the Chézy friction coefficient [$m^{1/2}/s$];

3.2.2 Assumptions

The use of Saint-Venant equations is based on following assumptions:

1. The width and depth is much smaller than the length of the river. This assumption is based on the realistic state of the river, under this assumption, lateral distribution can be neglected and pressure distribution is hydrostatic (Besson et al., 2005).
2. The bed slope of the river is small, i.e. $\sin \theta \approx \tan \theta$ (θ is inclination angle of the riverbed), which means the variation of the height is very small. Under this assumption the vertical dimension of the water motion can be removed from the water system,
3. The fluid is incompressible gradually varied flow and streamline curvature is small. In addition, formulas related to steady flow (e.g. Manning Formula and Chézy Formula) can be used to estimate the effect of friction.
4. Only gravity force is taken into consideration. Which means Coriolis force can be neglected.

3.2.3 Discretization of the Saint-Venant equations

We noticed that the Saint-Venant equations are consisted of a group of partial differential equations (PDE). One simple way to implement a PDE model is to discretize it into several ordinary differential equations (ODE), by substituting the space derivatives with their corresponding finite differences (Petroni, 2010).

According to Stelling and Duinmeijer (Stelling and Duinmeijer, 2003), the discretization of Saint-Venant equations is based on a staggered computational grids with the assumption that the river width W [m] is constant and the cross section area is approximated to rectangular. The river model is discretized into N sections along the flow direction with the length $\Delta x = \frac{L}{N}$, where L is the total length of the river.

The computational grid, illustrated in Figure 3-1, consists of pressure and velocity points. The organization of the grid is based on Arakawa-C grid (Arakawa and Lamb, 1977). There are two types of grid points in the grid: the pressure point in odd number and the velocity in even number.

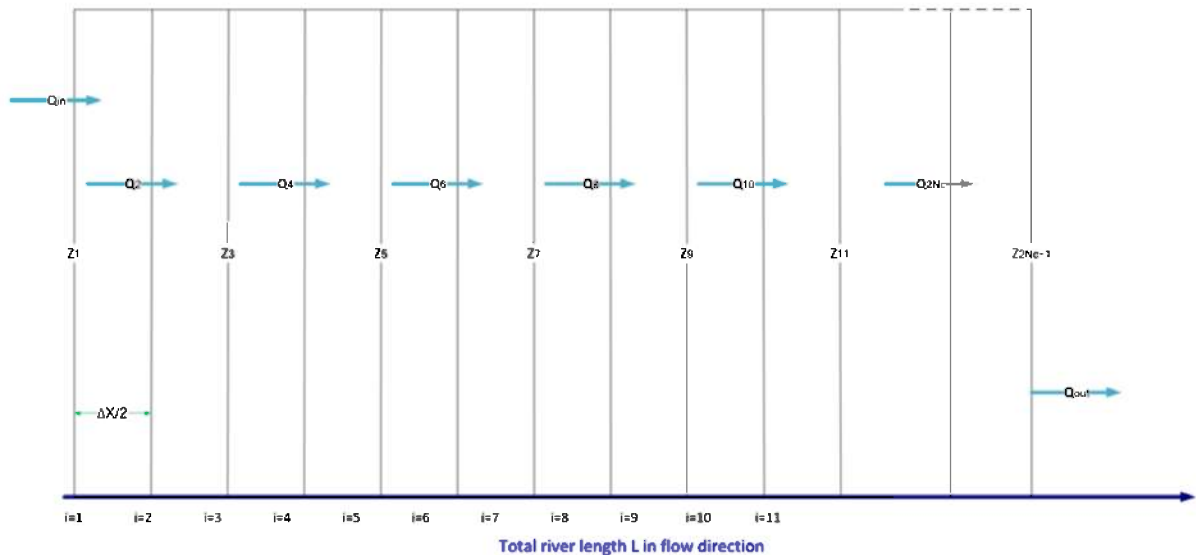


Figure 3-1: The one-dimension staggered grid for Grønvollfoss Power Plant modeling and simulation

In order to simplify the model, the assumptions of river width and cross section are made. The river width W is constant while the cross section area A is considered rectangular.

$$W(x, t) = W \quad \text{Equation 3-3}$$

$$A(x, t) = W \cdot Z(x, t) \quad \text{Equation 3-4}$$

Under these assumptions, the river width W can be isolated from the time derivative of cross section. This reduced the complexity of the discretization and the water level should be considered a state variable.

3.2.3.1 Discrete continuity equation

Define mass balance equation as

$$\frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out} \quad \text{Equation 3-5}$$

Where, m is the notation of mass.

Applying the mass balance to the cell around grid point $i = 2n - 1$ ($n = 1, 2, 3, \dots$) and define

$$m = \rho \cdot A_i \cdot \Delta x_i \quad \text{Equation 3-6}$$

$$\dot{m} = \rho \cdot Q \quad \text{Equation 3-7}$$

$$A_i = W \cdot Z_i \quad \text{Equation 3-8}$$

We have,

$$\frac{d\rho \cdot A \cdot \Delta x_i}{dt} = \rho \cdot Q_{in} - \rho \cdot Q_{out} \quad \text{Equation 3-9}$$

$$\frac{d\rho \cdot W \cdot Z_i \cdot \Delta x_i}{dt} = \rho \cdot Q_{in} - \rho \cdot Q_{out} \quad \text{Equation 3-10}$$

$$\frac{dZ_i}{dt} = -\frac{Q_{out} - Q_{in}}{W \cdot \Delta x_i} \quad \text{Equation 3-11}$$

For the first pressure point ($i = 1$) and the cell around it, $\Delta x_i = \Delta x/2$, the continuity equation can be written as,

$$\frac{dZ_1}{dt} = -\frac{Q_2 - Q_{in}}{W \cdot \frac{\Delta x}{2}} \quad \text{Equation 3-12}$$

Similar to (5), applying to the rest of the pressure points $i = 2n + 1$ we have,

$$\frac{dZ_{2n+1}}{dt} = -\frac{Q_{2n} - Q_{2n-2}}{W \cdot \Delta x} \quad \text{Equation 3-13}$$

3.2.3.2 Discrete momentum equation

Define momentum balance equation as:

$$\frac{dM}{dt} = \dot{M}_{in} - \dot{M}_{out} + \sum F \quad \text{Equation 3-14}$$

Where, M is momentum and F is the combination of pressure, friction and gravity force, the influence of other forces are neglected due to the assumption in Section 1.2.2.

Applying the momentum balance to the cell around grid point $i = 2n$ ($n = 1, 2, 3, \dots$) and define

$$M = m \cdot v = \rho \cdot A_i \cdot \Delta x_i \cdot \frac{Q}{A_i} \quad \text{Equation 3-15}$$

$$\dot{M} = m \cdot v = \rho \cdot Q \cdot \frac{Q}{W \cdot Z_i^2} \quad \text{Equation 3-16}$$

$$\sum F = \Delta F_{pressure} + \Delta F_{gravity} + \Delta F_{friction} \quad \text{Equation 3-17}$$

$$\begin{aligned} \Delta F_{pressure} &= F_{pressure_{in}} - F_{pressure_{out}} \\ &= \int p_{in} - p_{out} dA = W \cdot P_a \cdot (Z_{in} - Z_{out}) + \frac{W}{2} \cdot \rho \cdot g \\ &\quad \cdot (Z_{in}^2 - Z_{out}^2) \end{aligned} \quad \text{Equation 3-18}$$

$$\Delta F_{gravity} = F_{gravity_{in}} - F_{gravity_{out}} = -\rho \cdot A \cdot \Delta x_i \cdot g \cdot \sin \theta \quad \text{Equation 3-19}$$

$$\Delta F_{friction} = \frac{g \cdot |Q_{in}| \cdot Q_{in}}{C^2 \cdot W \cdot R \cdot \bar{Z}^2} \quad \text{Equation 3-20}$$

Where,

- p pressure;
- P_a standard atmospheric pressure;
- \bar{Z} defined as the average of Z_{in} and Z_{out} :

$$\bar{Z} = \frac{Z_{in} + Z_{out}}{2} \quad \text{Equation 3-21}$$

For the first velocity point ($i = 2$) $\Delta x_i = \Delta x/2$, the momentum equation can be written as:

$$\frac{dQ_2}{dt} = \frac{Q_{in}^2}{\Delta x \cdot W \cdot Z_1^2} - \frac{(Q_2 + Q_4)^2}{4 \cdot \Delta x \cdot W \cdot Z_3^2} + \frac{W \cdot P_a \cdot (Z_1 - Z_3)}{\rho \cdot \Delta x} + \frac{W \cdot g}{2 \cdot \Delta x} \cdot (Z_1^2 - Z_3^2) + \frac{(Z_1 + Z_3)}{2} \cdot g \cdot \sin \theta + \frac{g \cdot |Q_2| \cdot Q_2}{C^2 \cdot W \cdot R \cdot \frac{(Z_1 + Z_3)^2}{4}}$$

Equation 3-22

Similarly, applying to the rest of the velocity points $i = 2n$ we have:

$$\frac{dQ_{2n}}{dt} = \frac{(Q_{2n-2} + Q_{2n})^2}{4 \cdot \Delta x \cdot W \cdot Z_{2n-1}^2} - \frac{(Q_{2n-2} + Q_{2n})^2}{4 \cdot \Delta x \cdot W \cdot Z_{2n+1}^2} + \frac{W \cdot P_a \cdot (Z_{2n-1} - Z_{2n+1})}{\rho \cdot \Delta x} + \frac{W \cdot g}{2 \cdot \Delta x} \cdot (Z_{2n-1}^2 - Z_{2n+1}^2) - W \cdot \frac{(Z_{2n-1} + Z_{2n+1})}{2} \cdot g \cdot \sin \theta + \frac{g \cdot |Q_{2n}| \cdot Q_{2n}}{C^2 \cdot W \cdot R \cdot \frac{(Z_{2n+1} + Z_{2n-1})^2}{4}}$$

Equation 3-23

Now, we have the general form of the discretized Saint-Venant equations.

$$\left\{ \begin{array}{l} \frac{dZ_{2n+1}}{dt} = -\frac{Q_{2n} - Q_{2n-2}}{W \cdot \Delta x} \\ \frac{dQ_{2n}}{dt} = \frac{(Q_{2n-2} + Q_{2n})^2}{4 \cdot \Delta x \cdot W \cdot Z_{2n-1}^2} - \frac{(Q_{2n-2} + Q_{2n})^2}{4 \cdot \Delta x \cdot W \cdot Z_{2n+1}^2} + \frac{W \cdot P_a \cdot (Z_{2n-1} - Z_{2n+1})}{\rho \cdot \Delta x} + \frac{W \cdot g}{2 \cdot \Delta x} \cdot (Z_{2n-1}^2 - Z_{2n+1}^2) - W \cdot \frac{(Z_{2n-1} + Z_{2n+1})}{2} \cdot g \cdot \sin \theta + \frac{g \cdot |Q_{2n}| \cdot Q_{2n}}{C^2 \cdot W \cdot R \cdot \frac{(Z_{2n+1} + Z_{2n-1})^2}{4}} \end{array} \right.$$

3.3 Model of the Segment Gate

As described in Chapter 2, a segment gate is used to control the outflow and water level of the power plant. In Grønvollfoss Power Plant, the flow through the segment gate is natural flow because the water elevation of two side of the gate.

To calculate the discharge of the segment gate, a simplified equation provided by NVE has been used.

$$Q = k \cdot a \cdot b \cdot \sqrt{2 \cdot g \cdot H}$$

Equation 3-24

Where,

- Q is the discharge through the segment gate [m^3/s].
- k the contraction coefficient;
- a the opening height of the gate [m];
- b the width of the gate [m];
- g the gravitational acceleration [m/s^2];
- H the energy head upstream the gate [m].

The value of a and b can be obtained by the drawing of the segment gate provided by Skagerak Energi, see Figure 3-2 and Figure 3-3.

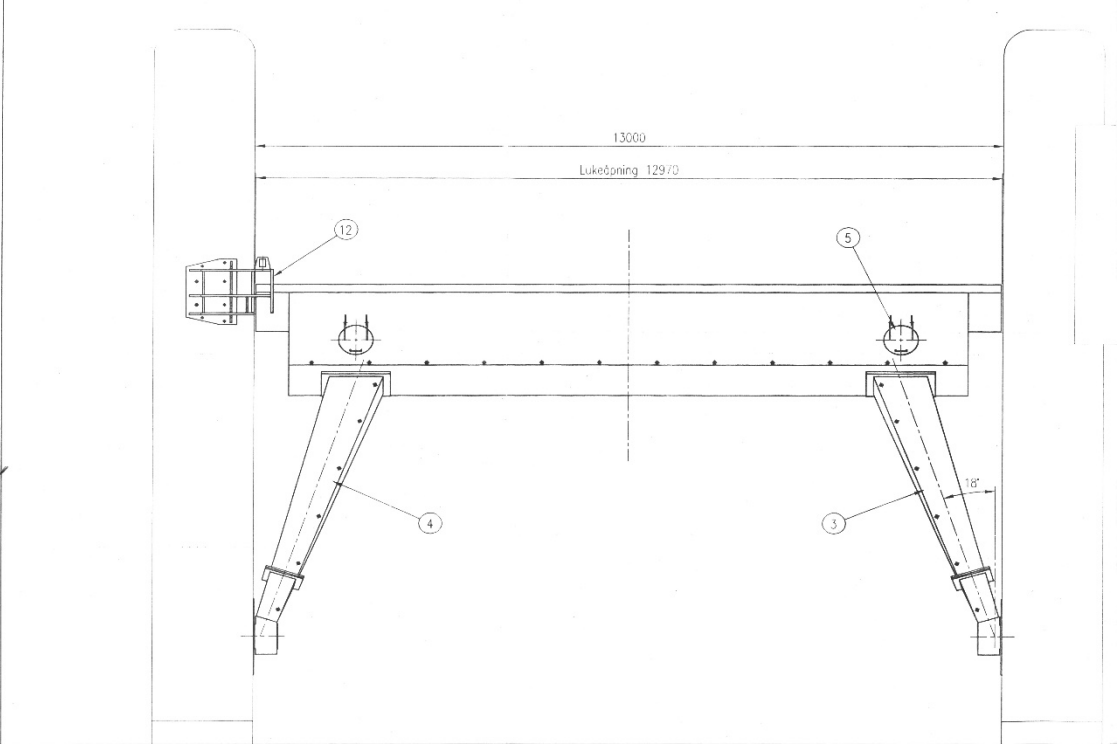


Figure 3-2: A Plan view of the segment gate used in Grønvollfoss Power Plant. (Image source: Skagerak Energi, Norway)

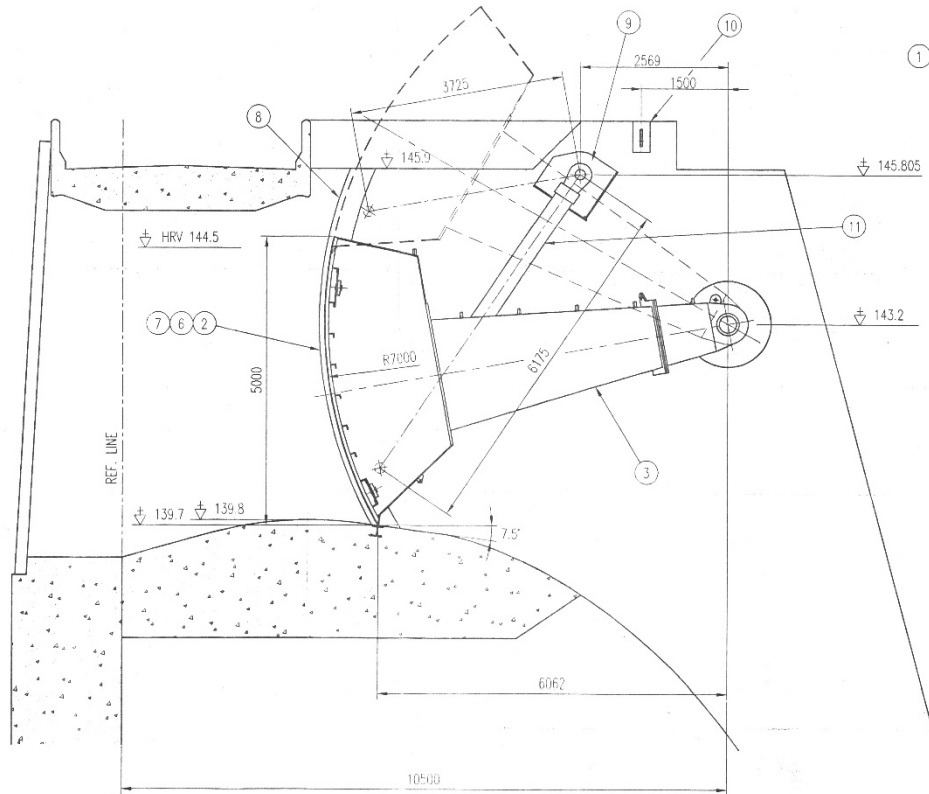


Figure 3-3: Drawing of the segment gate used in Grønvollfoss Power Plant. (Image source: Skagerak Energi, Norway)

From the figures above, the values of parameters of the segment gate can be obtained, see Table 3-1.

Table 3-1: Parameters of the segment gate.

Parameter	meaning	value
a	Gate opening height	$144.5 - 139.7 = 4.8 \text{ m}$
b	Width	13 m
H	Energy head	$144.5 - 143.2 = 1.3 \text{ m}$
g	Gravitational acceleration	9.81 m/s^2
k	Contraction coefficient	0.857

According to NVE, the contraction coefficient k is equal to 0.7 for a typical segment gate. However, for the segment gate in Grønvollfoss Power Plant, k can be obtained by following calculation.

The segment gate in Grønvollfoss Power Plant has a maximum outflow of $270 \text{ m}^3/\text{s}$ at opening of 100%. Skagerak Energi has provided the plot of outflow versus opening. See the Figure 3-4.

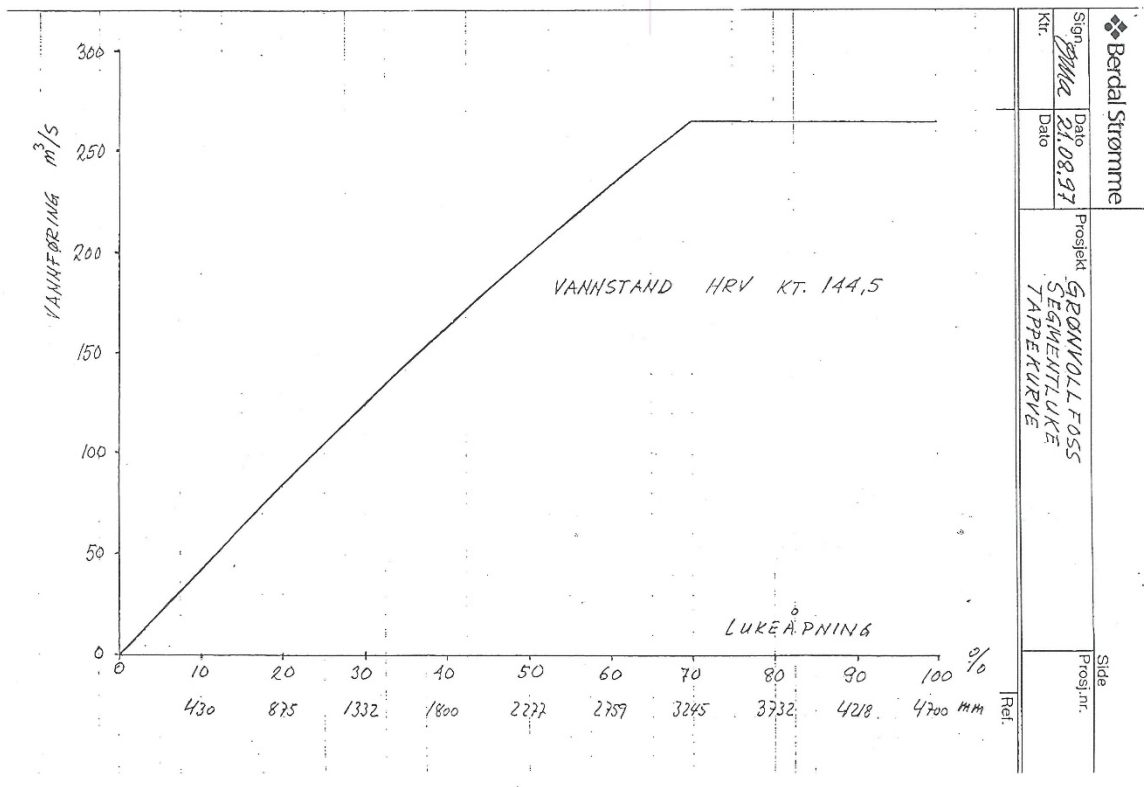


Figure 3-4: Plot of outflow VS gate opening of the segment gate in Grønvollfoss Power Plant. (Image source: Skagerak Energi, Norway)

The contraction coefficient k can therefore be calculated by:

$$k = \frac{Q_{max}}{a_{max} \cdot b \cdot \sqrt{2 \cdot g \cdot H}} \quad \text{Equation 3-25}$$

$$k = 0.857$$

Thus, the maximum discharge of the segment gate is given by:

$$Q = k \cdot a \cdot b \cdot \sqrt{2 \cdot g \cdot Z}$$

$$Q_{max} = 0.857 \cdot a_{max} \cdot 13 \text{ m} \cdot \sqrt{2 \cdot 9.81 \text{ m/s}^2 \cdot 1.3 \text{ m}} \quad \text{Equation 3-26}$$

$$Q_{max} = 270 \text{ m}^3/\text{s}$$

3.4 Model validation

In order to ensure that the model gives reasonable information about the system been modeled, validation to the model is therefore a necessary step. To validate the model, a step signal had been sent as an input to the model. By observing the response from the model, we can decide if the model represent and correctly reproduce the behaviors of the real water level system.

3.4.1 Model response

When simulate the model with setting the segment gate to closed and stop the power generation unit, which means the outflow of the plant is zero, the model gives a response as shown in Figure 3-5. From the figure, we can see the water level keeps increasing as the gate remains closed. Note that the simulation is performed to the general water level model instead of the model of Grønvollfoss, such that there is no constraint for highest and lowest regulation level.

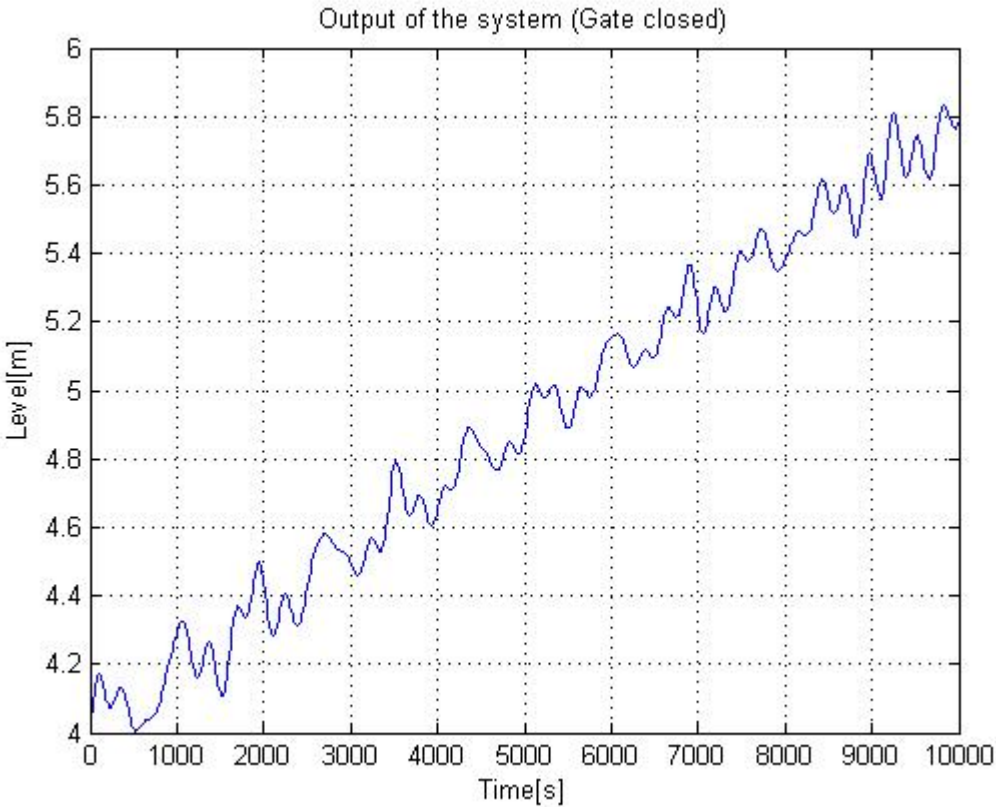


Figure 3-5: Model response with the gate closed.

When setting the opening of segment gate to maximum at $t = 6000\text{ s}$, it can be observed from Figure 3-6 that the level start to decrease at $t = 6000\text{ s}$.

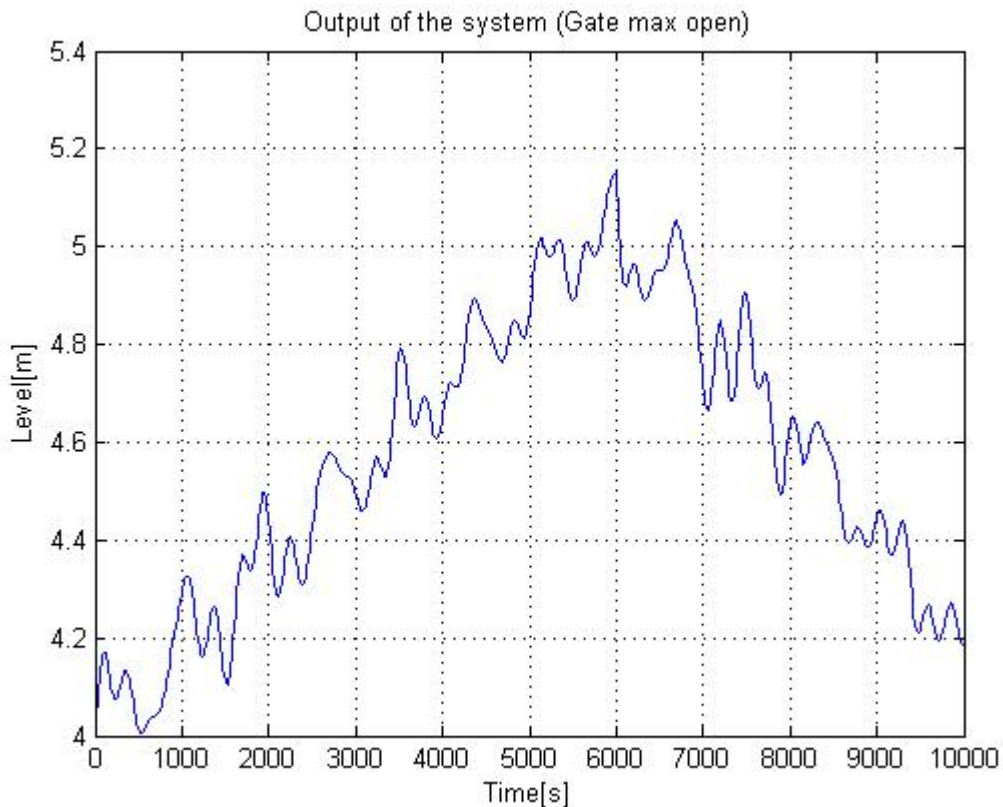


Figure 3-6: Model response with the maximum opening of the gate.

From the response of the water level model, we can see the model correctly reproduced the behaviors of the real water level system.

3.5 Open loop simulation for water level model of Grønvollfoss Power Plant

To study the dynamic behavior of the water level of the power plant, we need to carry out the open loop simulation. The words “open loop simulation” means simulation without a controller. MATLAB was used as a tool to perform the dynamic simulation. Varying parameters and conditions are tested in the simulation. To compare the results, the simulation was carried out at two conditions of the inflow situation. They are:

- Normal inflow.
- High inflow.

Normal inflow is the situation of Grønvollfoss Power Plant ordinary running in. High inflow is to simulate the running of the power plant under irregular conditions like flooding or raining. The responses to the different conditions had been recorded and analyzed.

3.5.1 Behavior of water level under normal inflow condition

When Grønvollfoss Power Plant running in normal operation condition, the water level of the pondage is about 4 m. Two Kaplan turbines are utilizing 112 m³/s for power production.



Figure 3-7: Flow rate for power production units.

As described in the beginning of this chapter, the river model is discretized into N sections along the flow direction and the input states of the model are water levels and inflow rates at

each section. Due to the lack of accurate measurement data for each of the section and for simplification, we assume the level of river is 4 m and inflow rate is 120 m³/s (inflow for power production is not included). Under these conditions, the simulation result is shown in Figure 3-8.

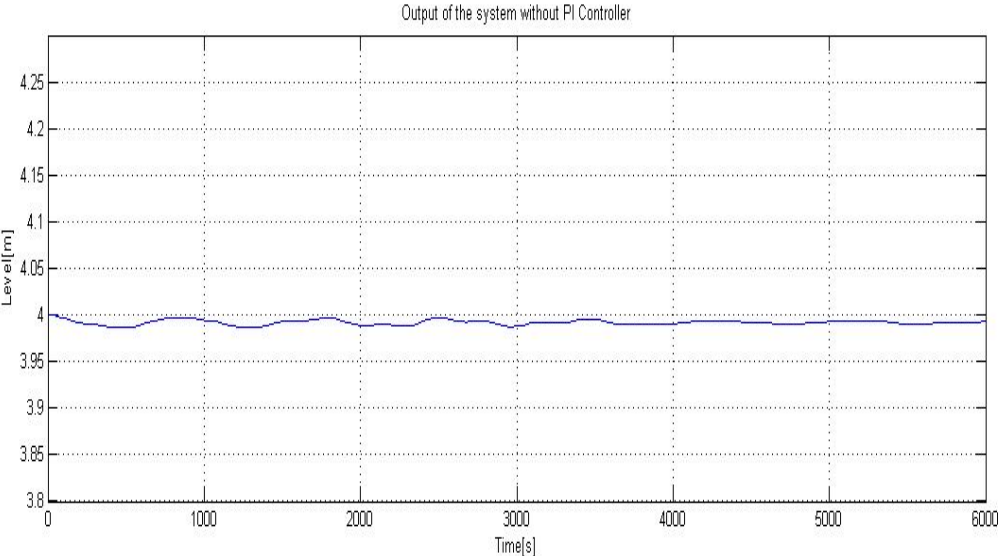


Figure 3-8: Open loop simulation of the dynamic water level model.

It can be observed that the water level is close to 4 m, the tiny slope of the riverbed causes the difference. It is also worth noting that the behavior of water level presented by the model is dynamic. For a real water system, the level is unsteady because of the continuous flowing of water. Thus, the model represented the interactions between adjacent sections and reproduced the behaviors of the real water level system.

3.5.2 Behavior of water level under high inflow condition

As described in Chapter 2, there are many reasons can cause irregular flow of the pondage of Grønvollfoss Power Plant, however, flooding is the most frequent problem to the plant. In Norway, flooding is monitored and forecasted by NVE - the Norwegian Water Resources and Energy Directorate. NVE has measurement stations all over the land of Norway and recording real-time hydrological data. Unfortunately, there is no measurement station can provide hydrological data for Grønvollfoss Power Plant, the simulation under high inflow condition has to be carried out under an assumption of inflow rate.

Assume the inflow rate is 350 m³/s for flooding, the simulation result is shown in Figure 3-9. There are two responses curve shown in the figure, the blue line represents the behavior of the initial section of the pondage, while the red line is the response of the output water level of the model.

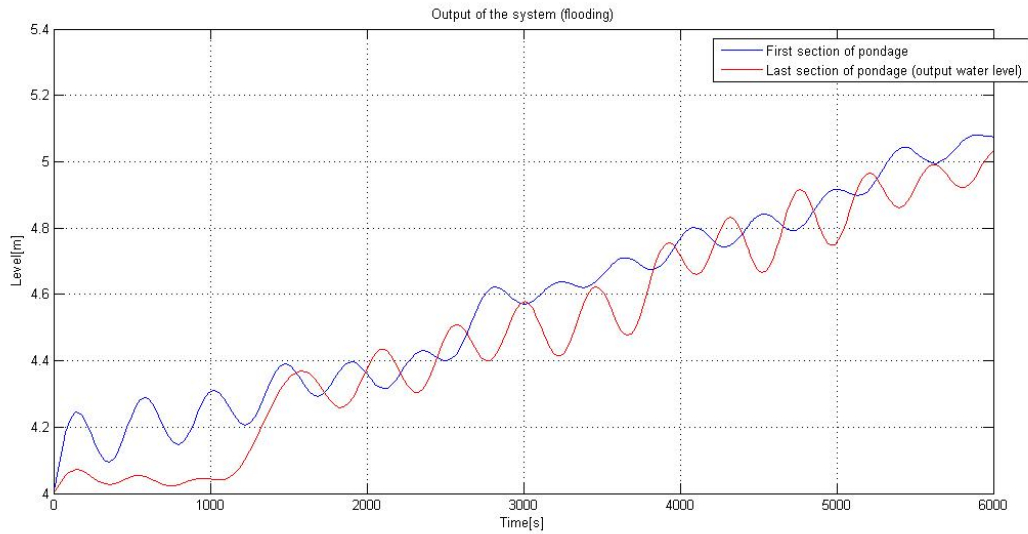


Figure 3-9: Open loop simulation of the dynamic water level model under flooding condition.

It is worth noting that the water level of first section started to rise at beginning of the simulation, while a significant upraise of the water level in last section appeared at around $t = 1200$ s. The time interval proved again that the model based on Saint-Venant equations reproduced the interactions between adjacent sections of the water system; the time was taken for the flooding flowing from the first to the last section.

4 Control of water level in run-of-river power plant

This chapter mainly describes the purpose of developing the control system for Grønvollfoss power plant. PI controller has been implemented in this system. The result of simulation with controller has been presented and discussed.

4.1 Control requirement and objective

In a typical run-of-river hydro power plant, keeping as high water fall as possible is essential for ensure the most power production. The total installed capacity of Grønvollfoss is 32 MW (16 MW for each turbine), which produce 172 GWh each year in average. For every 1 cm the level up streams can be kept closer to the maximum level, there is an annual saving of approx. 25000 NOK.

Meanwhile, an excess level of waterfall may cause waste of power, running in low water fall may cause insufficient power output of the unit, so there must be constraints for the minimum and maximum flow of water in the river to prevent the level is too high or too low.

The upper plant, Årlifoss, also influences the water flow. Downstream from Årlifoss provides inlet flow to the pondage of Grønvollfoss, which can be considered as disturbance. If the control action is not taken in response of the disturbance, the set point level cannot be maintained and it may influent the power production.

The main objective of developing the control system is to:

- Keep the water level within the constraints and as high as possible to maximize the revenue while guarantee the normal operation of the plant.
- Response quickly and accurately to the change of flow, maintain the set point level when disturbance happened.

4.2 Three-position controller

Traditional control of floodgate is manually operating with three-position controller. The basic algorithm of three-position controller is to response to the different between the set point and current water level. The controller consists of three control actions:

1. Off The controller will take no action to the gate.
2. Open The controller will increase the opening of the gate.
3. Close The controller will decrease the opening of the gate.

Three-position controller is a simple and easy to use controller. It can perform basic control to the water level. However, the disadvantage of the three-position controller is significant, the control action is based on current level, which means the controller cannot make full use of the model and take action in advance

4.3 PI controller

4.3.1 Introduction to PI controller

PI (Proportional Integral) controller is a traditional controller widely used in industrial control system. The controller consist of two terms: proportional term and integral term. The controller calculate the difference between set point (also called “reference value”) and measurement value as error signal, and adjust the input signal according to the error signal to stabilize the system.

The basic form of PI algorithm is given by:

$$u(t) = K_p e(t) + \frac{1}{T_i} \int e(\tau) d\tau \quad \text{Equation 4-1}$$

Where,

- K_p is the proportional gain
- T_i is the integral gain
- e is the error
- t is the time
- τ is the variable of integration

Equation 4-1is the general continuous time domain description of PI controller. The general block diagram of a feedback control system is shown in Figure 4-1.

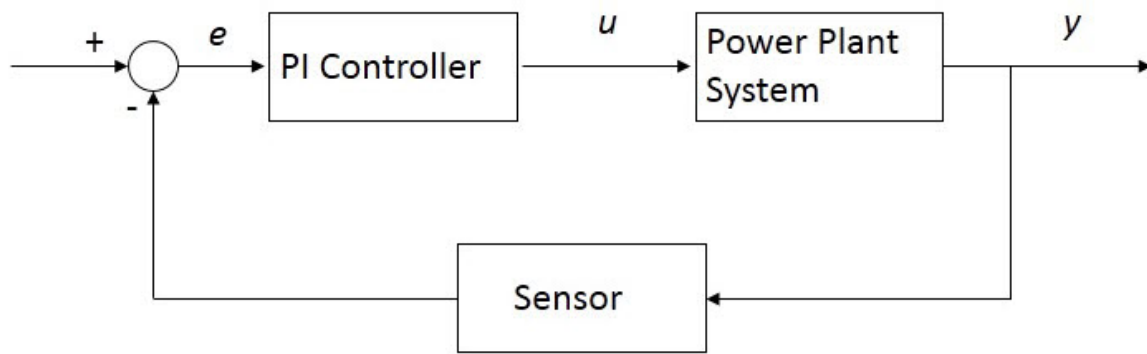


Figure 4-1: Block diagram of a feedback control system.

4.3.2 Continuous time state space PI controller

With reference to Figure 4-1, the control input u can be written as:

$$u = K_p \cdot \left(1 + \frac{1}{T_i s}\right) \cdot e \quad \text{Equation 4-2}$$

$$u = K_p \cdot e + \frac{K_p}{T_i s} \cdot e \quad \text{Equation 4-3}$$

Define controller states as:

$$z = \frac{K_p}{T_i s} \cdot e \quad \text{Equation 4-4}$$

$$s \cdot z = \frac{K_p}{T_i} \cdot e \quad \text{Equation 4-5}$$

Apply inverse Laplace transformation on it gives:

$$\dot{z} = \frac{K_p}{T_i} \cdot e \quad \text{Equation 4-6}$$

The inverse Laplace transformation been used is:

$$L^{-1}(sz(s)) = \dot{z} = \frac{dz}{dt} \quad \text{Equation 4-7}$$

Therefore, we have the continuous-time state-space model for the PI controller:

$$u = K_p \cdot e + \dot{z} \quad \text{Equation 4-8}$$

$$\dot{z} = \frac{K_p}{T_i} \cdot e \quad \text{Equation 4-9}$$

4.3.3 Tuning of PI controller

To tune the parameters of PI controller, I followed the Good Gain method developed by Finn Haugen. The values of PI parameters obtained by Good Gain method have been used as the initial value. A finely tune of these values has then been carried out by trial and error method.

An overview of the zone-based procedure is given by:

1. Set integral gain T_i to infinity
2. Set proportional gain K_p low for system stability
3. Apply a step command
4. Adjust the value of K_p until some overshoot and a barely observable undershoot can be seen, see Figure 4-2. Denote the gain value as K_{pGG} .
5. Set the integral gain T_i equal to $T_i = 1.5 \cdot T_{ou}$. Here T_{ou} is the time interval between the overshoot and undershoot, see Figure 4-2.
6. Set $K_p = 0.8 \cdot K_{pGG}$ respond to the introduction of I-term.

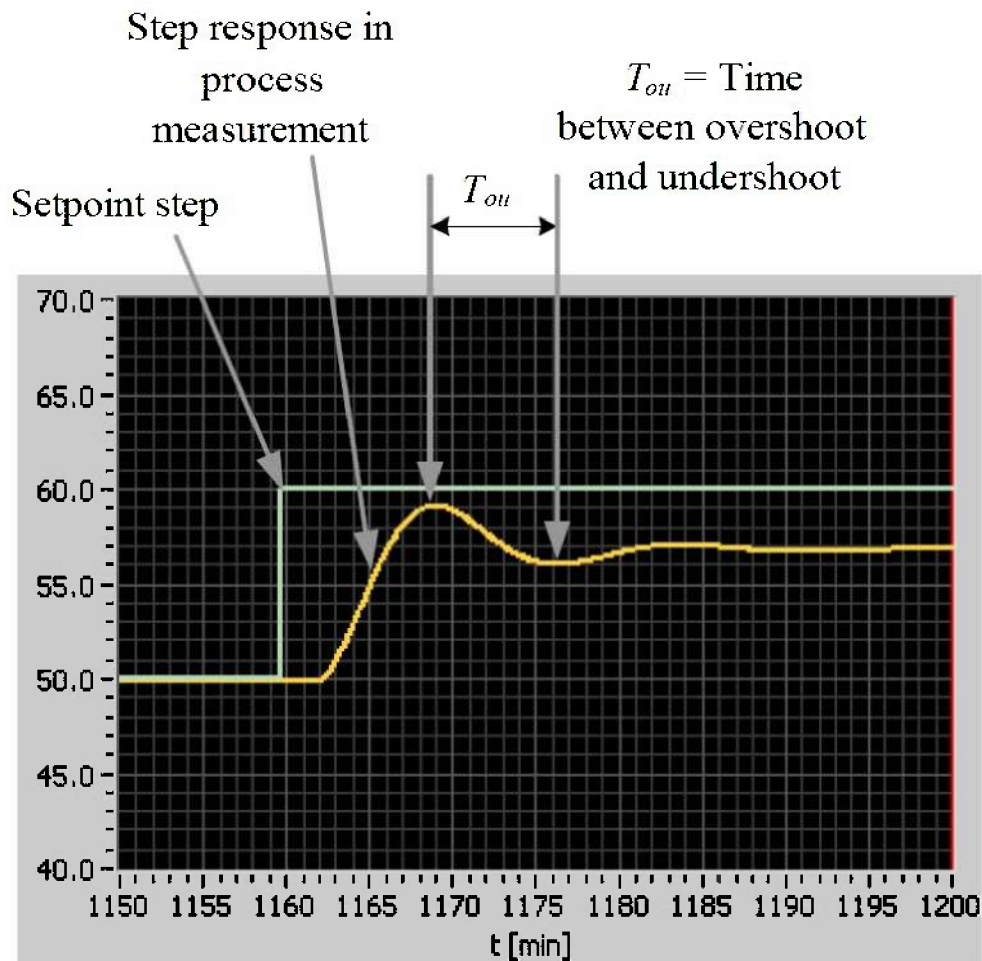


Figure 4-2: The Good Gain method: Reading off the time between the overshoot and undershoot of the step response with P controller. (Haugen, 2010)

4.3.4 Anti-windup

Large excitations of the control system may cause the control signal to reach its maximum or minimum limits with the control error being different from zero. The summation of numerical integration will cause the input signal u to increase (or decrease) steadily – this is denoted integral windup – such that the input signal u may get a very high (low) value. When the excitations are back to normal values, it may take a very long time before the large value of u is integrated back to a normal value, causing the process output to deviate largely from the set point (Haugen, 2012).

In the practical implementations of PI controller, there may be reasons for handling constraints on the control input u . These constraints may be physical limitations of the controller organ. Hence, the practical and physical control input u should lie within the hardbound constraints as $u_{min} \leq u \leq u_{max}$

When the controller input u is within the bounds, we are using the controller state equation:

$$u = K_p \cdot e + \dot{z} \quad \text{Equation 4-10}$$

$$\dot{z} = \frac{K_p}{T_i} \cdot e \quad \text{Equation 4-11}$$

However, when the controller are saturated like $u \leq u_{min}$, we set $u = u_{min}$ and $\dot{z} = 0$.

Similarly, when $u \geq u_{max}$. We set $u = u_{max}$ and $\dot{z} = 0$.

The anti-windup function has been implemented in MATLAB.

4.4 Simulation with PI controller

4.4.1 Parameters setup

The simulation with PI controller is performed with model parameters as shown in Table 4-1. Due to the lack of measurement data, some of these parameters are approximation

Table 4-1: Simulation parameters.

<i>Parameter</i>	<i>Meaning</i>	<i>Value</i>
W	The width of the river	100 <i>m</i>
L	The length of the river	5000 <i>m</i>
A	The cross sectional area	400 <i>m</i> ²
P_w	The wetted perimeter	108 <i>m</i>
P	Standard atmospheric pressure	101325 <i>Pa</i>
ρ	Density of water	1000 <i>kg/m</i> ³
θ	Slope of the river bed	0.0114 <i>degree</i>
g	The gravitational acceleration	9.81 <i>m/s</i> ²

4.4.2 Simulation with constant set point

In the first instance, the simulation with PI controller is performed with constant reference signal. The initial water level is set to 4 m and the inflow is put to 130 m³/s. The desired water level is set to 4.01 m. The setup of the initial values are listed in Table 4-2.

Table 4-2: Setup of the initial values for constant reference water level simulation.

Parameters	Value
Initial water level	4 m
Constant inflow rate	130 m ³ /s
Reference water level	4.01 m
Simulation time step	Decided by the solver
Simulation time	20000 seconds

The set point is set to 4.01 m due to the requirement of Skagerak Energi. It is required that the water level is controlled at ±1 cm. The result of simulation is shown in Figure 4-3.

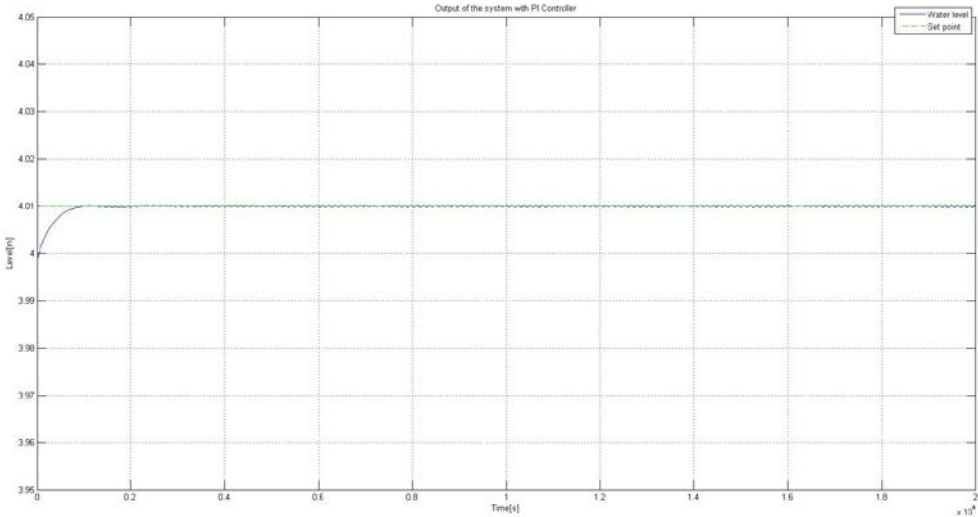


Figure 4-3: Output signal of the simulation with PI controller (constant reference $u = 4.01m$).

In Figure 4-3, we can see the water level reaches the desired set point in around 1000 seconds, and then stabilizes at around $t = 1300 s$ after the overshoot and undershoot. As description document provided by Skagerak Energi, the control delay of Grønvollfoss Power Plant is

approximately 25 minutes. Due to the length of the pondage is 5 kilometers, where there is change to reference signal, it takes relatively longer time (approximately 25 minutes) to see the control action in response to the reference signal. Therefore, the controller should be tuned in a way that it takes approximately 25 minutes (1300 seconds) to reach the set point and stable. As it shows in the figure, the controller is tuned to reproduces the control delay and the water level is well controlled at 4.01 *m*.

4.4.3 Simulation in changing reference signal

For a run-of-river power plant, we may want to raise the water level to achieve more power production rate, or lower the level to reduce the risk of the water level hazard. Therefore, the following simulation has been carried out with the change of reference water level.

Table 4-3: Setup of the initial values for changing reference water level simulation.

<i>Parameters</i>	<i>Value</i>
Initial water level	4 <i>m</i>
Constant inflow rate	130 <i>m</i> ³ / <i>s</i>
1 st reference water level	4.01 <i>m</i>
2 nd reference water level	3.99 <i>m</i>
3 rd reference water level	4 <i>m</i>
Simulation time step	Decided by the solver
Simulation time	40000 <i>seconds</i>

According to the setup of the reference signal, the set point is set to take step changes at different simulation time. As we can see from Figure 4-4, the first step change from 4 *m* to 4.01 *m* occur at $t = 10000$ *s*. Next, at $t = 20000$ *s*, the set point changes to 3.99 *m*. Finally, at $t = 30000$ *s*, the set point changes back to 4 *m* again.

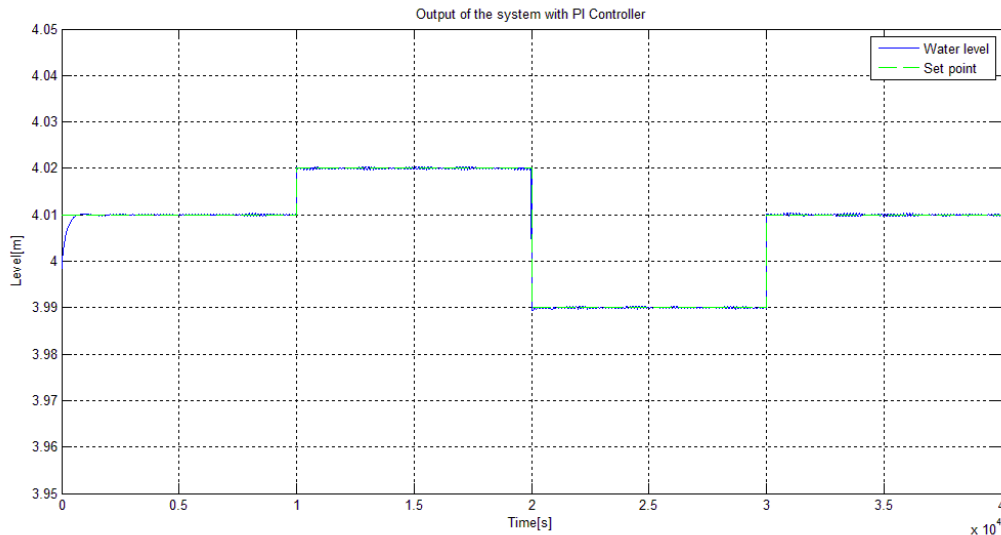


Figure 4-4: Output signal of the simulation with PI controller (changing reference).

Based on the plot of the water level simulation, we can see the water level stable at the desired value under the control action of the controller. We notice that the control delay, which has been discussed in the last section, appeared at the beginning of the simulation. However, it cannot be observed at following step changes. One possible reason for this phenomenon might be that the discrete time by the solver is too short, which resulted in the excessive quick responding to the reference change. The output signal is the water level of the last section of the pondage; it is directly attached to the segment gate. Therefore, when the control action is taken to the segment gate, the water level of the last section is the first to take a change. In reality, the segment gate is not possible to be opened or closed such fast, thus, the simulation result cannot fully represent the behavior of the real water level system.

4.4.4 Simulation in changing disturbance

One of the requirements of the controller is to deal with the disturbances. Main reasons causing the disturbances are:

1. Change of the incoming flow from upstream power plant Årlifoss.
2. Flooding from the river Tinnelva.
3. Rainfall over the pondage.

All of the reasons above can cause the disturbance to the inflow. To observe the response to the disturbance with PI controller, the simulation has been performed under changing of inflow. The setup of simulation parameters are shown in Table 4-4.

Table 4-4: Setup of the initial values for water level simulation with disturbance.

Parameters	Value
Initial water level	4 m
Initial inflow rate	130 m ³ /s
Inflow rate under disturbance	250 m ³ /s
Reference water level	4 m
Simulation time step	Decided by the solver
Simulation time	40000 seconds

Here the inflow rate is changed at $t = 10000$ s from $130 \text{ m}^3/\text{s}$ to $250 \text{ m}^3/\text{s}$ and return back to normal inflow rate $130 \text{ m}^3/\text{s}$ again after $t = 30000$ s. The reference level is set to 4 m because the aim of the simulation is to maintain the normal water level under the disturbance.

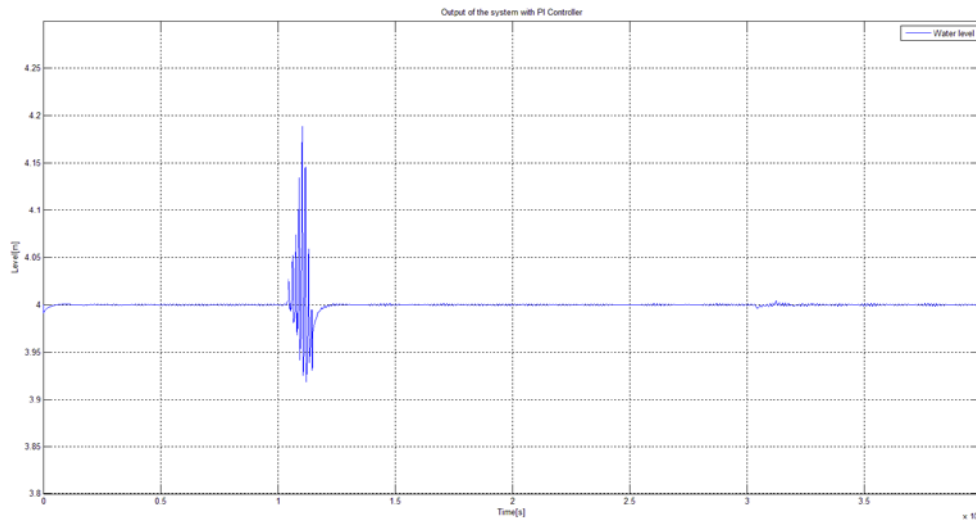


Figure 4-5: Output signal of the simulation with PI controller (under disturbance).

As we can see from Figure 4-5, the water level started to oscillate after applying the disturbance to the inflow rate. The highest overshoot is around 0.18 m over the set point and the lowest undershoot is around 0.07 m below the set point. At $t = 30000$ s, the inflow rate is set back to normal, a very small overshoot can be observed.

The objective of the simulation with changing disturbance is to observe the behavior of the water level when irregular inflow occurred. It can be seen from the result that, when facing the irregular inflow, the oscillation of water level is inevitable, the effective measure is to

bring the level back to normal as fast as possible and keep the level stable. As we can see from Figure 4-5, the time duration it takes to control and stabilize the water level is less than 1800 s (half hour), considering the control delay, the controller satisfy the requirement of the power plant.

5 Conclusion

5.1 Conclusion of the model

The model of the run-of-river power plant consists of the model of the model of water level and the model of segment gate. The water level model was developed based on the Saint-Venant equations stemming from the mass and momentum conservation. In addition, the discretization of the model in space has been carried out using staggered grid, which provided a group of ordinary differential equations. Several assumptions has been made to simplify the calculation, which includes the constant width, constant slope of riverbed, and constant cross-section area, etc. Model validation has been performed to confirm the model can represent and correctly reproduce the behaviors of the real water level system, especially the interactions of adjacent sections. When provided with measurement data, the model can theoretically be tuned and apply on not only Grønvollfoss Power Plant but also any open-channel shallow water system with sensible assumption.

The model of floodgate is developed based on the design of the gate. According to the description of the plant, the floodgate been considered in this thesis is segment gate. The anticipation of the gate model is to enable the controller regulate the opening of the gate in degree. However, in the realistic application, sometimes the segment gate is working with other gates. For the convenient of calculation, flow rate is selected to be the controlled variable instead of opening degree.

The mathematical model of the run-of-river power plant has been implemented and simulated in MATLAB. Open loop simulation was performed; the result of dynamic behavior of the water level was studied and analyzed. Due to the lack of measurement data, the plan to test the model with realistic parameters cannot be carried out, further measurements needs to be done to obtain enough data for model testing.

5.2 Conclusion of the control

For the control of the run-of-river power plant, simulations with PI controller under three different conditions have been performed. During the simulations, the control action taken by the controller can stabilize the water level at desired set point. The control delay of the system can be observed, the control strategies were able to meet and fulfill the control requirement. When I simulated the system under varying reference signal, the controller responses are too fast comparing with realistic power plant. One reason is the solver I used in MATLAB is “ode15s”, the solver is based on Runge - Kutta Method and the solver itself defines the

discrete time step. To slow it down, one option is to use the “ode4” solver, the solver allow user define the time step, as a result, the accuracy of the simulation will be reduced.

The objective of the controller is to control the water level within $\pm 1 \text{ cm}$ of set point and response fast to the disturbance, as we can see from the result of simulation, the controller fulfilled the goal. However, the control model can be used to determine the potential highest HRV and achieve higher power production rate. Further experiment can be done under accurate measurements.

6 Further work

The model-based control of run-of-river power plant is a broad topic. Despite the tasks has been done in this thesis, there are still a lot of works remained to be investigated and fulfilled. The works that can be done with advantage in the future for deep study are highlighted as followed:

- The water level model can be more accurate and realistic by considering the influence of partial flow.
- The cross-section area is assumed as a rectangle in this model. Consider a trapezoid of a combination of triangle and rectangle.
- The solver used in simulation is ode15s, the time step is too short for the power plant. Consider another solver or use Forward Euler Method to define time step.
- Develop a sensible linearized model and apply Modern controllers such as model predictive controller.
- Design a low pass filter to reduce the measurement noise.
- Modeling of the upstream power plant Årlifoss can be done by the same way as in this thesis. Årlifoss influence the inflow rate of Grønvollfoss, in order to optimize the total power production of these two plants, the model of coordinate operation can be developed based on the models of two power plants.
- Update the model according to the real measurements of water level and flow rate.
- Test the model with different disturbance based on the different flow rate and water level according to the seasons.

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Appendices

Appendix A Task Description



Telemark University College

Faculty of Technology

FMH606 Master's Thesis

Title: Model based control of run-of-river power plant Grønvollfoss

TUC supervisor: Bernt Lie

External partner: Skagerak Kraft, Ingvar Andreassen

Task description:

The following tasks are of interest:

1. Give an overview of run-of-river hydro power plants, and in particular of the power plants along river Tinnelva.
2. Develop a model of the dynamics of water level in run-of-river pondages/dams. (E.g. the Saint-Venant model, which is based on mass and momentum balance.) Particular emphasis should be put into how to solve the model numerically. Also consider models for the gates, which are part of the boundary conditions for the (distributed) run-of-river model. The model should be verified to give sensible results.
3. Discuss available information (measurements) from the Grønvollfoss power plant, and consider model calibration and model validation.
4. Discuss requirements for control of the Grønvollfoss power plant. (Set-point, constraints, etc.).
5. Consider a linearized model of the Grønvollfoss power plant, and study the use of traditional control algorithms to control the level and the production.
6. Consider the use of MPC for local control of the Grønvollfoss power plant.
7. Discuss how control of the Grønvollfoss plant is influenced by the control of the upstream Årlifoss plant, and whether there is a gain in coordinating the operation.
8. Document the work in a report.

Task background:

Skagerak Energi is operating two run-of-river hydro power plants in river Tinnelva flowing out of lake Tinnsjøen in Eastern Telemark. The uppermost, Årlifoss, has a 16.2 m high water fall, and provides inlet flow to the pondage of Grønvollfoss, which is in question here. Grønvollfoss is situated 5 km downstream from Årlifoss, and has a water fall of 22.6 m. The installed power in Grønvollfoss is 2x16 MW (i.e. two turbines), and the average annual production is 172 GWh.

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In run-of-river hydro power plants, it is important to keep as high water fall as possible to ensure the most power production. For Grønvollfoss powerplant this means that there is an annual saving of approx. 25 000 NOK for every 1 cm the level up streams can be kept closer to the maximum level.

At the same time, the level must not be too high. There are also constraints on the minimum flow of water in the river.

A particular problem with a sequence of run-of-river power plants is that they utilize the same water, so it is important to coordinate their operation to maximize the total power production.

With a change in water flow out of the upper plant, Årlifoss, there is a delay of some 25 minutes before this change in flow reaches the level at Grønvollfoss – the delay does depend on the flow, though. In order to manipulate the level in the Grønvollfoss magazine, there are three different types of gates with different capacities, and different characteristics (slew rates, etc.). In addition there are some flood gates.

It is of interest to study the dynamics of the water level in the dam, depending on the inflow from Årlifoss, as well as the production in Grønvollfoss and possible bypass flow. It is furthermore of interest to study how to operate the Grønvollfoss power plant in such a way that the production is maximized while satisfying the constraints of the operation.

Student category:

Although the modeling part of the thesis as well as basic “process control” can be handled by any PT, EET, and SCE student, some topics such as model based control (MPC, state estimation, etc.) are specialities of SCE students. Thus it is an advantage to have SCE background. Furthermore, it is an advantage to have some knowledge of hydro power engineering, e.g. through the course Modeling and Simulation of Hydro Power Systems.

Practical arrangements:

The working place will be Telemark University College, Campus Kjølnes in Porsgrunn. Necessary information will be provided by Ingvar Andreassen/Skagerak Kraft.

Signatures:

Student (date and signature): February 1. 2013
Supervisor (date and signature): February 1, 2013 Bent di

Appendix B

MATLAB codes

```
%%*****
%%Author: Yiyang Ruan
%%Date: 13/02/2013
%%File Name: st_venant.m
%%*****

function dxdt=st_venant(t,x,g,L,W,Q_in,Q_out,Pa,rho,C,R,theta,K,Ti,ref)
N = size(x,1); %Number of states
Nc = N/2; %The total number of reaches
ZZ = x(1:Nc); %State of level
QQ = x(Nc+1:N-1);%State of flow rate
Kp =10000*K;

%Changing reference
%if t>=10000 && t<20000
% ref=ref+0.01;
%end

%if t>=20000 && t<30000
% ref=ref-0.02;
%end

%Changing disturbance
if t>=10000 && t<30000
    Q_in=350
end

%PI controller
z = x(N);
y = ZZ(Nc);
e = y-ref;
u = Kp*e+Kp*z;
%u = Kp*e;
Q_out = u;
if Q_out>=270
    Q_out=270;
    dzdt = 1;
end
if Q_out<=0
    Q_out=50;
    dzdt =1;
end
dzdt = 1/Ti*e;

assignin('base','ut',Q_out);
evalin('base','uc=[uc ut];');
```

```

%The loop iteration
%Configurations
% if t>5
%   Q_in = Q_in*1.1;
% end
dx = L/Nc-1;           %The step of reaches
fZZ = zeros(Nc,1); %build a vector to store dz/dt
fQQ = zeros(Nc-1,1); %build a vector to store dQ/dt

%Boundry Condition
fZZ(1) = -2*(QQ(1)-Q_in)/(W*dx);
fZZ(Nc) = -2*(Q_out-QQ(Nc-1))/(W*dx);
fQQ(1) = (Q_in^2)/(W*dx*ZZ(1)^2)-(QQ(1)+QQ(2))^2/(4*dx*W*ZZ(2))+...
(W*Pa)/(rho*dx)*(ZZ(1)-ZZ(2))+(g*W)/(2*dx)*(ZZ(1)^2-ZZ(3)^2)-...
g*(ZZ(1)+ZZ(3))/2*sin(theta)-
g*QQ(1)*abs(QQ(1))/(C^2*W*R*((ZZ(1)+ZZ(3))/2)^2);

%main iteration
for i=2:Nc-1
    if i<=Nc-2
        fZZ(i) = -(QQ(i)-QQ(i-1))/(W*dx);
        fQQ(i) = (QQ(i-1)+QQ(i))^2/(4*W*dx*ZZ(i)^2)...
        -(QQ(i)+QQ(i+1))^2/(4*dx*W*ZZ(i+1))+ (W*Pa)/(rho*dx)*(ZZ(i)-
ZZ(i+1))...
        +(g*W)/(2*dx)*(ZZ(i)^2-ZZ(i+1)^2)-g*(ZZ(i)+ZZ(i+1))/2*sin(theta)...
        -g*QQ(i)*abs(QQ(i))/(C^2*W*R*((ZZ(i+1)+ZZ(i-1))/2)^2);
    else
        fZZ(i) = -(QQ(i)-QQ(i-1))/(W*dx);
        fQQ(i) = (QQ(i-1)+QQ(i))^2/(4*W*dx*ZZ(i)^2)...
        -(QQ(i)+Q_out)^2/(4*dx*W*ZZ(i+1))+ (W*Pa)/(rho*dx)*(ZZ(i)-ZZ(i+1))...
        +(g*W)/(2*dx)*(ZZ(i)^2-ZZ(i+1)^2)-g*(ZZ(i)+ZZ(i+1))/2*sin(theta)...
        -g*QQ(i)*abs(QQ(i))/(C^2*W*R*((ZZ(i+1)+ZZ(i-1))/2)^2);
    end
end
end

dxdt = [fZZ;fQQ;dzdt];

```

```

%%*****
%%Author: Yiyang Ruan
%%Date: 13/02/2013
%%File Name: SV.m
%%*****
%Loop Simulation for

close all;
clear all;
clc

%Configuration of initial condiction
L = 5000; %The total length of the river [m]
W = 80; %The width of the river [m]
C = 76.42; %The Chezy friction coefficient [m1/2 per second]
%H = 13.7; %The water level of selected cross section [m]
S = 50; %The side slope of trapezoid
A = 800; %(W-H/S)*H/2; %The wetted cross sectional area [m2]
Pw = 100; %The wetted perimeter [m]
R = A/Pw; %The hydraulic radius [m]
g = 9.81; %Gravitational acceleration [m/s2]
Pa = 101325; %Standard atmospheric pressure
rho = 1000; %Density of the water
theta = 0.1/180*pi; %Degree
uc = [];
ut = 0;

%Boundary conditions
Q_in = 130; %Upstream by Arlifoss
Q_out = 130; %Outflow to turbine

%PI controller parameters
K = 60;
Ti = 180;
ref = 4;

%solver
t_end = 40000; %time span
x0 = [4*ones(11,1);130*ones(10,1);0.013];
%load('initx','x0');
stv = @(t,x) st_venant(t,x,g,L,W,Q_in,Q_out,Pa,rho,C,R,theta,K,Ti,ref);
[T,Y] = ode15s(stv,[0,t_end],x0);
%figure(1)
%plot(T,Y(:,1:6),'b',T,Y(:,1),'ob',T,Y(:,6),'xb');
%figure(2)
%plot(T,Y(:,7:11),'b',T,Y(:,7),'ob',T,Y(:,11),'xb');
%sp = 4.01*ones(1064,1);
%sp = [U;4.02*ones(2279-1064,1)];
%sp = [U;3.99*ones(3459-2279,1)];
%sp = [U;4.01*ones(4720-3459,1)];
figure(3)
plot(T,Y(:,11))
%plot(T,Y(:,11),T,sp,'g--')
legend('Water level','Set point')
xlabel('Time[s]');

```

```

ylabel('Level[m]');
title('Output of the system with PI Controller');
grid on;
Y(:,11)

%%*****
%%Author: Yiyang Ruan
%%Date: 13/02/2013
%%Without Controller
%%*****

function dxdt=sv_model(t,x,g,L,W,Q_in,Q_out,Pa,rho,C,R,theta)
N = size(x,1); %Number of states
Nc = (N+1)/2; %The total number of reaches
ZZ = x(1:Nc); %State of level
QQ = x(Nc+1:N);%State of flow rate

%The loop iteration
%Configurations
% if t>5
%   Q_in = Q_in*1.1;
% end
dx = L/(Nc-1); %The step of reaches
fZZ = zeros(Nc,1); %build a vector to store dZ/dt
fQQ = zeros(Nc-1,1); %build a vector to store dQ/dt

%Boundry Condition
fZZ(1) = -2*(QQ(1)-Q_in)/(W*dx);
fZZ(Nc) = -2*(Q_out-QQ(Nc-1))/(W*dx);
fQQ(1) = (Q_in^2)/(W*dx*ZZ(1)^2)-(QQ(1)+QQ(2))^2/(4*dx*W*ZZ(2))+...
(W*Pa)/(rho*dx)*(ZZ(1)-ZZ(2))+g*W/(2*dx)*(ZZ(1)^2-ZZ(3)^2)-...
g*(ZZ(1)+ZZ(3))/2*sin(theta)-
g*QQ(1)*abs(QQ(1))/(C^2*W*R*((ZZ(1)+ZZ(3))/2)^2);

%main iteration
for i=2:Nc-1
    if i<=Nc-2
        fZZ(i) = -(QQ(i)-QQ(i-1))/(W*dx);
        fQQ(i) = (QQ(i-1)+QQ(i))^2/(4*W*dx*ZZ(i)^2)...
        -(QQ(i)+QQ(i+1))^2/(4*dx*W*ZZ(i+1))+W*Pa)/(rho*dx)*(ZZ(i)-
ZZ(i+1))...
        +(g*W)/(2*dx)*(ZZ(i)^2-ZZ(i+1)^2)-g*(ZZ(i)+ZZ(i+1))/2*sin(theta)...
        -g*QQ(i)*abs(QQ(i))/(C^2*W*R*((ZZ(i+1)+ZZ(i-1))/2)^2);
    else
        fZZ(i) = -(QQ(i)-QQ(i-1))/(W*dx);
        fQQ(i) = (QQ(i-1)+QQ(i))^2/(4*W*dx*ZZ(i)^2)...
        -(QQ(i)+Q_out)^2/(4*dx*W*ZZ(i+1))+W*Pa)/(rho*dx)*(ZZ(i)-ZZ(i+1))...
        +(g*W)/(2*dx)*(ZZ(i)^2-ZZ(i+1)^2)-g*(ZZ(i)+ZZ(i+1))/2*sin(theta)...
        -g*QQ(i)*abs(QQ(i))/(C^2*W*R*((ZZ(i+1)+ZZ(i-1))/2)^2);
    end
end
dxdt = [fZZ;fQQ];

```

Appendix C

Simulation result of the open loop simulation

The figures in the appendix represent the state of the simulation. The first figure is the flow rate of the each section of the pondage. The second figure is the water level of the each section of the pondage. The curve marked in “o” symbol means the first section, while the curve marked in “x” symbol means (Arakawa and Lamb, 1977, Arud, 2013, Baidu Baike, 2013, Besson et al., 2005, De Schutter and Scattolini, 2011, Erbiditi, 2004, Farina et al., 2011, Flaspöhler, 2007, Haugen, 2010, Haugen, 2012, Kwagis Power, 2013, NVE, 2005, NVE and Ministry of Petroleum and Energy, 2003, Petrone, 2010, Ruan et al., 2013, Ruscio, 1996, Sánchez et al., 2010, Sayers, 1990, Skagerak Energi, 2009, Sleigh and Goodwill, 2000, Stelling and Duinmeijer, 2003, van’t Hof and Veldman, 2012, Wikipedia, 2013b, Wikipedia, 2013a, Xu et al., 2012, Xu et al., 2011, Xu et al., 2013, Zarmehi et al., 2011) the last section.

