NTNU – Trondheim
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Innovative Surge Systems for Small Hydro

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M.Sc. THESIS IN HYDRAULIC ENGINEERING

Candidate: Mr. Fredrik Staff Edin

Title: Innovative Surge Systens for Small Hydro

1. Background

In Norway regulation stability on isolated grid is not required for small hydropower plants (< 10 MW), compared to what is specified by STATNETT for large hydro. To satisfy this demand, larger hydropower plants often need surge tanks in order to ensure regulation stability. Small hydropower plants are most frequently constructed without such components.

The specified limit [MW] for securing of regulation stability is currently under discussion. Due to massive development of wind, small hydro and photovoltaic power projects, the amount of unregulated power in the common grid is increasing, and there is need for more stability in the grid. It is therefore possible that small hydro have to account for regulation stability in the future.

Small hydro is sensitive to costs, and the additional cost of a traditional surge tank may render many projects unfeasible. It is therefore interesting to investigate alternative solutions which can provide regulation stability for small hydro projects. This thesis will focus on measures which may be implemented in the waterway design.

2. Main questions for the thesis

The thesis shall cover, though not necessarily be limited to the main questions listed below.

2.1 Literature and desk study

The candidate shall carry out a literature study of regulation stability theory, and existing solutions to ensure regulation stability.

2.2 Main tasks

The candidate must collect available background material such as former studies, reports and publications. Related to this material the following must be carried out:

1 Review of existing solutions
2 Select potential solutions suitable for small hydro
3 Evaluation of the selected solutions through case-studies
4 Conclusions
5 Proposals for future work
6 Presentation

3 Supervision and data input

Professor Leif Lia and PhD candidate Kaspar Vereide will supervise and assist the candidate, and make relevant information available.

Discussion with and input from colleagues and other research or engineering staff at NTNU is recommended. Significant inputs from other shall be referenced in a convenient manner.

NTNU

The research and engineering work carried out by the candidate in connection with this thesis shall remain within an educational context. The case-studies are regarded as study objects, and the candidate and the supervisors are therefore free to introduce assumptions and limitations which may be considered unrealistic or inappropriate in a contract research or a professional context.

4 Report format, references and contract

The master contract must be signed not later than 15. January. The report should be written with a text editing software, and figures, tables, photos etc. should be of good quality. The report should contain an executive summary, a table of content, a list of figures and tables, a list of references and information about other relevant sources. The report should be submitted electronically in B5-format .pdf-file in DAIM, and three paper copies should be handed in to the institute.

The executive summary should not exceed 450 words, and should be suitable for electronic reporting.

The Master's thesis should be submitted within Wednesday 10th of June 2015.

Trondheim 15. January 2015

Leif Lia

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Abstract

The Nordic grid quality is stated to be unsatisfactory in regards to the quality of frequency. The increasing amount of unregulated hydropower, interconnecting cables and increased flow of power on the grid are reasons given by Statnett SF (2014).

If the stability of the grid is to be improved, small hydropower plants may be required to provide stable energy to the grid, a requirement that small hydropower plants have been exempt from.

Achieving regulation stability for small hydropower is found to be achievable with the same toolkit as is used for large hydropower. Open or closed surge chamber, increased conduit area, increased amount of rotating masses and heating elements or modern variants of such as hydrogen production are all transferable to small hydropower. In addition, a responsive bypass valve is proposed as a new solution which will achieve regulation stability at the cost of water loss.

The optimal solutions will vary for every hydro power plant and is very dependent on the hydrology, topography and the design choices of the hydro power plant. This master thesis studies two cases, Usma (9.98 MW) which is an existing power plant and Storvatnet (1.4 MW) which has received its license. Both cases may be required to achieve regulation stability if the legislation regarding small hydro power plants are changed. A generalized method for achieving regulation stability is proposed and used for the two cases.

A key financial ratio is proposed as a comparison tool for power plants, which are required to achiever regulation stability. The additional cost of achieving regulation stability is divided by the total amount of provided power in kWh.

For Usma a closed surge chamber solution in steel was found to be the optimal solution. The cost of regulation stability for Usma were found to be 0.26 $\frac{NOK}{kWh}$ which will result in 5 % of the total cost of the power plant. For the second case, Storvatnet, the cost of regulation stability for was found to be 0.06 $\frac{NOK}{kWh}$ where the optimal solution were a closed surge chamber made in steel. These two cases were compared to an estimated cost of an existing large hydropower plant, Tonstad which has four closed surge chambers estimated at a cost of 0.08 $\frac{NOK}{kWh}$.

Sammendrag

Statnett SF (2014) sier at frekvenskvaliteten av det nordiske nettet ikke er tilfredsstillende. En økende andel uregulert kraftproduksjon, sjøkabler og økt flyt av strøm på nettet er årsaken til den reduserte frekvenskvaliteten.

For å øke frekvensstabiliteten på nettet kan det kreves at små vannkraftverk må forsyne nettet med stabil strøm, ett krav som små vannkraftverk for øyeblikket er unntatt.

Små vannkraftverk kan oppnå regulering stabilitet ved å bruke de samme metodene som blir brukt for store vannkraftverk. Åpne eller lukkede svingekammere, økt tverrsnitt av vannveien, økte roterende masser i systemet, varmekjeler eller andre moderne varianter som hydrogenproduksjon er alle brukbare løsninger som også vil fungere for små vannkraftverk.

Den optimale løsningen for reguleringstabiliteten for små vannkraftverk vil variere for hvert kraftverk på grunn av forskjeller i hydrologi, topografi og de valg av design som blir gjort. Denne master oppgaven tar for seg to små vannkraftverk, det eksisterende kraftverket Usma (9.98 MW) og konsesjons godkjente Storvatnet (1.4 MW). Begge kraftverkene kan bli nødt til å oppnå regulering stabilitet dersom kriteriene for små vannkraftverk forandres.

For å sammenligne de ulike løsningene foreslås det å bruke nøkkeltallet for kostnader knyttet til anskaffelse av reguleringstabiliteten delt på strømproduksjonen i kWh over ett år.

For Usma er den optimale løsningen ett lukket svingekammer konstruert i stål. Nøkkeltallet for reguleringstabiliteten for Usma ble estimert til å være 0.26 $\frac{NOK}{kWh}$ som tilsvarer 5 % av totalkostnadene for kraftverket. Den optimale løsningen for Storvatnet ble også funnet til å være et lukket svingekammer konstruert i stål. Kostnaden ble estimert til 0.06 $\frac{NOK}{kWh}$. Disse to løsningene ble sammenlignet med det eksisterende kraftverket Tonstad (960 MW), som har 4 lukkede svingekammer i fjell som har en estimert kostnad på 0.08 $\frac{NOK}{kWh}$.

Acknowledgment

A huge thank goes to Kaspar Vereide and Leif Lia for the support and teaching that they have provided in regards to this master thesis.

Appreciation also goes to Bjørnar Svingen and Torbjørn Nielsen who shared their expertise and time in order to help me.

I would also like to thank TrønderEnergi and Sweco, the accuracy of the simulations of Usma would not be possible without their help.

And lastly, thanks to Mette S. Haugen who listened passionately to the the ramblings of hydropower plants, surge chambers and the frustrations of writing a masters thesis.

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1 Introduction

To ensure that the frequency of the power grid is stable and constant during changes in power consumption, the power plants have to regulate their power production. Deviations between power produced and consumed on the grid will cause an increase or decrease of the power grids frequency. If the power production is higher than the power consumption the frequency will increase and vice versa. The governor in a hydropower plant is a feedback system which measures the rotational speed of the turbine, and applies changes to the flow of water to minimize the deviation between the measured rotational speed and the rotational reference speed.

For a power plant to have sufficient regulation stability several criteria set by Statnett SF (2012) have to be met. A power plant which has sufficient regulation stability has to be able to change the flow of water without the risk of high water hammer pressure that increases above the systems design pressure. The water hammer pressure will be increased by the length of the conduit, so hydropower plants with long conduits may be troublesome. For these power plants, trying to reduce the energy production by reducing the discharge may in fact increase the energy produced because of the water hammers pressure increase. The opposite of the intended effect when trying to lower the water flow.

In the Statnetts report "System operation and market development plan 2014-20" the quality of frequency on the Nordic grid is said to be unsatisfactory. This was concluded by a ENTSO-E study of the Nordic grid. Statnetts report gives several reason for the negative trend of frequency quality (Statnett SF, 2014).

- Increased trade on the Nordic grid has caused an increased flow of power and larger, more frequent changes on the grid
- More interconnecting cables increase the intercontinental trade which results in larger, more frequent changes in the grid and higher structural imbalances
- Increased stress on the grid with more bottlenecks and smaller margins
- Reduced access of automatic reserves in periods with low load

In recent years an increased amount of unregulated wind-, photovoltaic- and small hydropower plants are dominating the production during times of low load, especially during the summer. These power plants will often have a limited ability to improve the frequency regulation which is causing considerable challenges for the Nordic grid in periods of low load. Statnett is expecting that the regulated power plants will make the

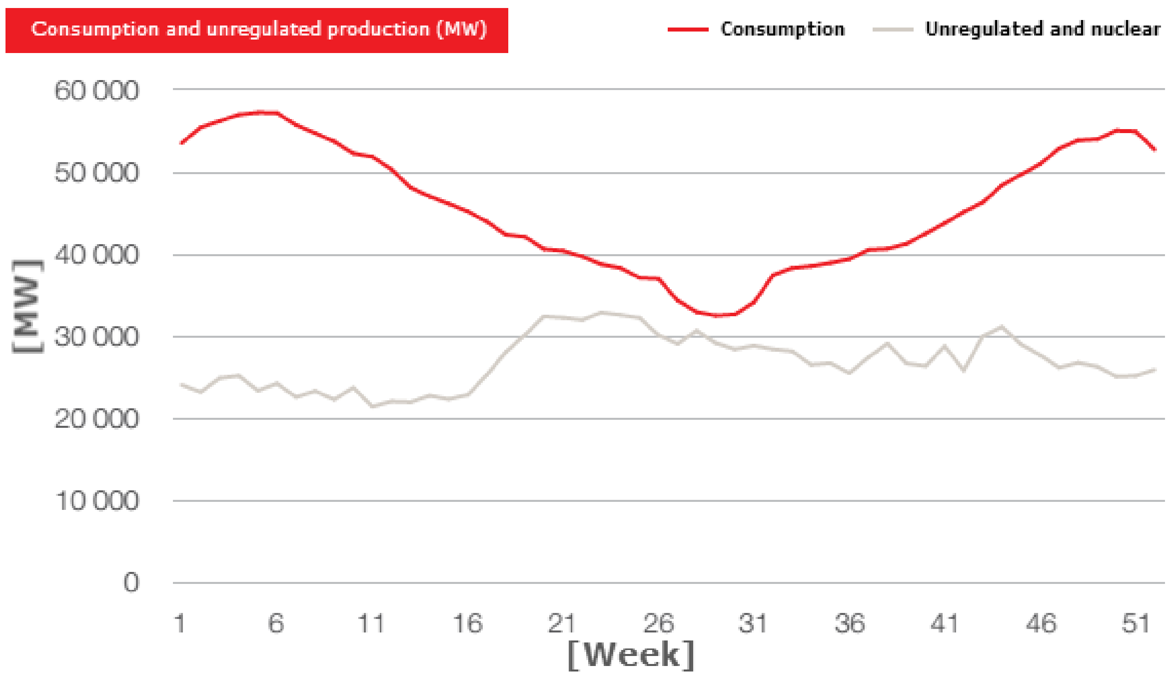


Figure 1.1.: *Expected relation of power consumption (red) and unregulated power production (grey) on the Nordic grid in 2020 (Statnett SF, 2014)*

most of the intercontinental power cables and export power during times with high power prices instead of periods of low load. Statnetts simulation for the year 2020 shows that during a summer the unregulated power production will be dominating in the Nordic grid, as shown in Figure 1.1 (Statnett SF, 2014).

Statnett has informed NVE of these challenge and proposed that if small power plants are in the future required to have frequency regulation then the stability of the grid can be increased during periods of low load (ibid.).

In addition, the Norwegian government has requested comments on the EU commission regulation on establishing a network code on requirements for grid connection of generators (European commission, 2015). Tveit (2015) has replied on behalf of the Norwegian small hydropower union in regards to the EU commissions regulation. In the letter he warns that stricter requirements for small hydropower in Norway will involve severe costs, especially if the regulation has an retroactive effect on existing small hydropower plants. The profit margins for small hydropower are already tight, and increased high construction costs may break projects because they are uneconomical.

It is expected that the same solutions which grant regulation stability for larger hydropower plants may be used for small hydropower as well. This study will examine the possible solutions specifically for small hydropower where innovative solutions are required to ensure successful projects. This study will also shed some light on the cost associated with a stricter requirement for regulation stability for small hydropower plants.

2 Theory

To analyze and evaluate regulation stability for small hydropower plants, understanding the basic theory regarding unsteady water flow in closed conduits is important. This chapter will give an introduction to the relevant theory and equations.

2.1. Water hammer

A water hammer occurs in closed systems when there occurs a change in the discharge due to the acceleration or retardation of the water masses. The water that is in motion and is subjected to a change will cause an increase in pressure due to the kinematic pressure of the water in motion. The elasticity of the water causes the change in motion to be propagated through the system with a speed equal to the speed of sound in the water filled string.

In a given system with no friction, the starting velocity will be u_0 at t_0. If the valve is closed instantly at t_0 then the time it will take for the shock wave to arrive at the closest water surface will be defined as a function of the length of the water string, L, and the speed of sound through water, c.

$$t_1 = \frac{L}{c} \; [s] \tag{2.1}$$

At the time t_1 the whole water string will be at rest and the shock wave will reach the basin where it will be reflected. The increased pressure that has built up in the system will reverse the flow velocity so that the water will be moving in the opposite direction that the flow had at t_0.

$$t_2 = \frac{2L}{c} \; [s] \tag{2.2}$$

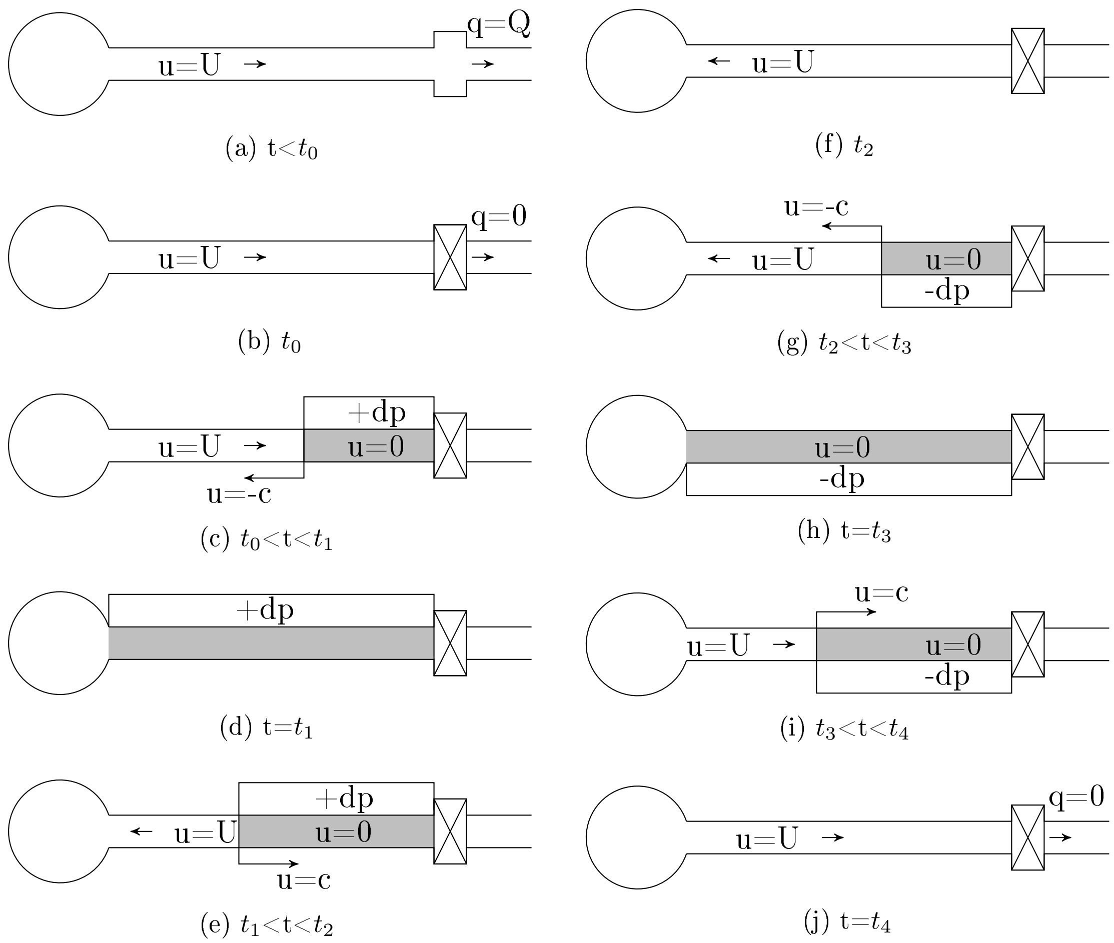
At t_2 the wave front will return to the valve while the water velocity is still negative. The shock wave will again be reflected, but due to the reversed water velocity the pressure will this time be negative.

$$t_3 = \frac{3L}{c} \; [s] \tag{2.3}$$

At t_3 the negative shock wave will be at the basin and reflected once more, after t_3 the water velocity will have the same direction of velocity as it had at t_0.

$$t_4 = \frac{4L}{c} \; [s] \tag{2.4}$$

Time t_4 marks the end of the period. In this example friction has been assumed to be zero, causing this cycle to be repeated forever. In a real system the increased pressure will be dissipated through friction in the conduit which will break the cycle and make the system static (Guttormsen, 2006).



(a) t<t_0 (b) t_0 (c) t_0<t<t_1 (d) t=t_1 (e) t_1<t<t_2 (f) t_2 (g) t_2<t<t_3 (h) t=t_3 (i) t_3<t<t_4 (j) t=t_4

Figure 2.1.: *Water hammer in a frictionless system*

2.1.1. Calculating the water hammer

Estimations of the pressure increase of a water hammer can be found by using the following equation which is derived from the momentum equation (Wylie, Streeter and Suo, 1993).

The momentum equation is applied to a control volume where the wavefront of the water hammer is moving to the left with an absolute speed of c - V_0 due to a small change in the valve setting. The pressure change is expressed as Δp and the velocity change as Δu. The resulting forces in the x component is equal to the time rate of increase of x momentum within the control volume with an addition of the net efflux of x momentum from the control volume. The volume of fluid having its momentum changed will be

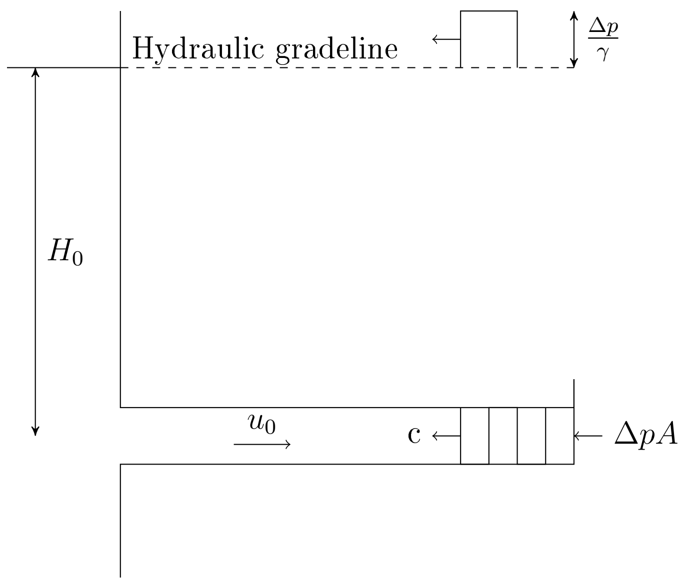


Figure 2.2.: *Instantaneous stoppage of frictionless liquid in horizontal pipe (Wylie, Streeter and Suo, 1993)*

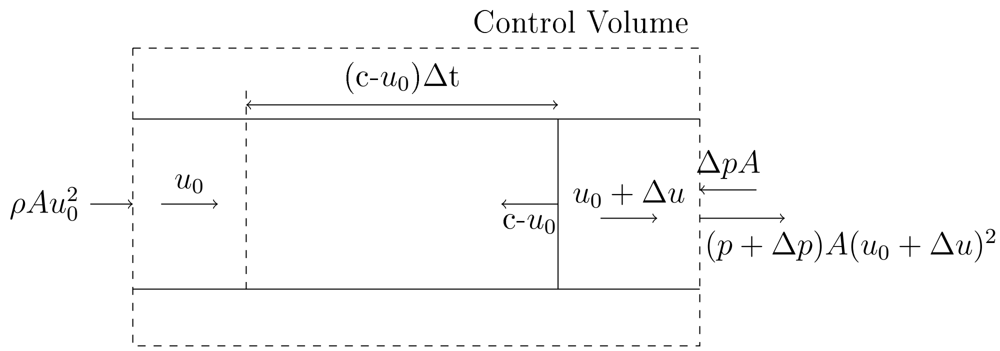


Figure 2.3.: *Momentum equation applied to control volume (Wylie, Streeter and Suo, 1993)*

$A(c-u_0)\Delta t$, so the time rate of increase of linear momentum will be:

$$\frac{A(c-u_0)\Delta t}{\Delta t}[(\rho+\Delta\rho)(u_0+\Delta u)-\rho u_0] \tag{2.5}$$

This yields the momentum equation:

$$-\Delta pA = A(c-u_0)[(\rho-\Delta\rho)(u_0+\Delta u)-\rho u_0]+(\rho+\Delta\rho)A(u_0+\Delta u)^2-\rho A u_0^2 \tag{2.6}$$

The net mass of the influx will equal to the time rate of increase of mass within the control volume, because of the conservation of mass. The same volume of fluid A(c-v_0)Δu will have its density changed so the equation becomes:

$$\rho A u_0 - (\rho+\Delta\rho)A(u_0+\Delta u) = \frac{A(c-u_0)\Delta t[(\rho+\Delta\rho)-\rho]}{\Delta t} \tag{2.7}$$

ρ = Mass density of fluid
$\Delta\rho$ = Incremental density change
g = Acceleration of gravity
γ = Specific weight of fluid = ρ g
Δp = Increment of pressure change
A = Cross-sectional area of pipe
u_0 = Initial velocity
Δu = Increment of flow velocity
c = Unknown wave speed

simplifying and combining Equation (2.7) with the momentum equation in Equation (2.6) gives the following basic equation:

$$\Delta p = -\rho c \Delta u \; [\frac{N}{mm^2}] \tag{2.8}$$

An incrimental change in pressure is $\Delta p = \rho g \Delta H$, so the head change,$\Delta H$, for the control volume will be:

$$\Delta H = -\frac{c\Delta u}{g} \; [mWC] \tag{2.9}$$

Which is more commonly known as the Joukowsky equation. The equation is valid if the valve is considered to be closed immediately. Immediately closing of the valve is defined as if the closing time, T_L, is less then half the time of the water hammer period, T_r. If it is considered that $T_L > T_r$, $\frac{T_r}{T_L}$ can be insert in Equation (2.9)

$$dh = \frac{cu}{g}\frac{T_r}{T_L} \; [mWC] \tag{2.10}$$

T_r is known and can be inserted in Equation (2.10) with the continuity equation $\Delta Q = uA$ to get:

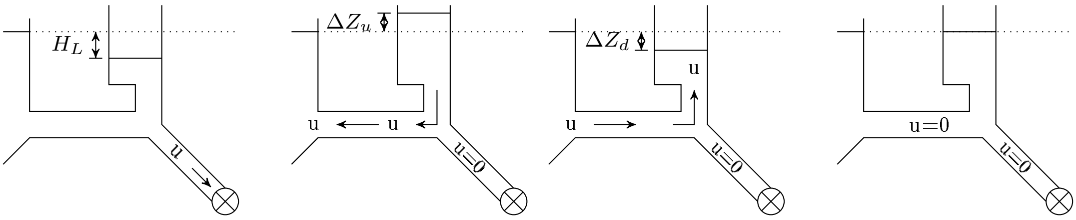
$$dh = 2\frac{\Delta Q}{T_L}\frac{L}{A} \; [mWC] \tag{2.11}$$

Equation (2.11) can be used to estimate the pressure increase caused by the water hammer effects.

2.2. Mass oscillations

To counteract high water hammer pressure and to increase the regulation stability, many hydropower plants introduce a free water surface closer to the turbine. This will decrease the length which is present in Equation (2.20) and (2.11). The introduction of a free water surface may solve the aforementioned problems of water hammer, but will introduce another phenomena: Mass oscillations in the conduit (Guttormsen, 2006).

Compared to the period of the water hammer the mass oscillations are slow. The effects of the water hammer will often be dissipated during the early development of the mass oscillations. The difference in periodicity between the two allows for separate computation for each phenomena. Nevertheless, the two actions do occur simultaneously (Rich, 1969).



(a) t=t_0 (b) t=$t_1, t_3, ...$ (c) t=$t_2, t_4, ...$ (d) t=t_∞

Figure 2.4.: *Mass oscillations in a system with a surge chamber*

Figure 2.4 illustrates a simplified system with an open surge chamber during load rejection. Head loss in the conduit from the basin to the open surge chamber is represented with H_L. At time t_0 the valve is immediately closed. The water in the penstock will be decelerated and eventually come to rest. If the water is considered to be non elastic then the penstock will essentially be plugged when the water comes to a rest. The incoming water through the conduit, coming from the basin, will be forced upwards to the open surge chamber transforming its kinetic energy to potential energy. If the level of the upsurge is higher than the level of the basin, the water flow will be reversed and result in a downsurge. This oscillation will repeat until the excess energy is dissipated through friction and the level of the open surge chamber is the same as in the basin (Guttormsen, 2006).

Estimating the maximum upsurge, ΔZ_u, can be done with a ±10% accuracy with the following equation (ibid.).

$$\Delta Z_u = \Delta Q \sqrt{\frac{\sum \frac{L}{A}}{g A_s}} \; [m] \tag{2.12}$$

A_s is the area of the surge chamber, ΔQ represents the difference in discharge and $\sum \frac{L}{A}$ is the sum of conduit lengths, L, divided by their representative area, A.

2.2.1. Stability of an open surge chamber

When an oscillation of the masses in the surge chamber has started, it is important that these oscillations are dampened over time. If this is not the case the surges can cause increasing and unwanted high oscillations in the system. To ensure the stability of a surge chamber Thoma proposed a stability criteria. His criteria, a minimum area for the the cross section of the rising water in the surge chamber will give stable mass oscillations in an open surge chamber (ibid.)

$$A_{Th} = \frac{LA}{2\alpha g H_e} \; [m^2] \tag{2.13}$$

H_e is equal to the effective height of the system, a is the area of the tunnel and α is the headloss coefficient which can be expressed with the formula

$$h_f = \alpha v^2 \tag{2.14}$$

By insertion of Equation (2.14) into Equation (2.13) the following is derived:

$$\alpha = \frac{L}{M^2 R^{\frac{4}{3}}} \tag{2.15}$$

The Thoma criteria can thus be expressed as

$$A_{Th} = \frac{M^2 R^{\frac{4}{3}} A}{2gH_e} \; [m^2] \tag{2.16}$$

which is valid for an open surge chamber. To calculate the necessary area of a closed surge chamber, also called a surge chamber or surge tank, the following criteria was deduced by Svee (1972).

$$A_{cr}^{air} = A_{Th}(1 + n\frac{P_{air}}{\rho g a_o}) \tag{2.17}$$

Where A_{cr}^{air} is the minimum area of the water surface in a closed surge chamber, A_{Th} is the minimum Thoma area of an open surge chamber, n is the adiabatic constant and which is assumed to be 1.4, P_{air} is the air pressure in the air cushion and a_0 is the distance between the surge chamber roof and the water level in a surge chamber with vertical walls and a horizontal roof.

A simplification of the minimum volume that a closed surge chamber has to have can be found with Equation (2.18), where V_0 is the necessary volume, h_{p0} is the absolute air pressure in the chamber and 1.4 is the adiabatic constant (Guttormsen, 2006).

$$V_0 = 1.4 \cdot h_{p0} \cdot A_{Th} \; [m^3] \tag{2.18}$$

The equation above is valid under the assumption that the air in the air cushion will respond adiabatically. According to Goodall et al. (1988) the typical closed surge chambers with normal geometry and periods (2 to 4 min) can be considered to respond adiabatically.

2.3. Friction in pipes

When water is traveling through a pipe the forces from the pipe surface will cause a head loss in the system due to friction. The calculation of the head loss was first proposed by Weisbach (1848) who introduced what would later be named the Darcy-Weisbach equation(2.19)

$$h_f = f\frac{L}{D}\frac{u^2}{2g} \; [m] \tag{2.19}$$

Where L is the pipe length, u is the water velocity, D is the pipe diameter and f is the pipe friction factor which is found by using the Moody diagram (Moody, 1944) shown in Figure 2.5.

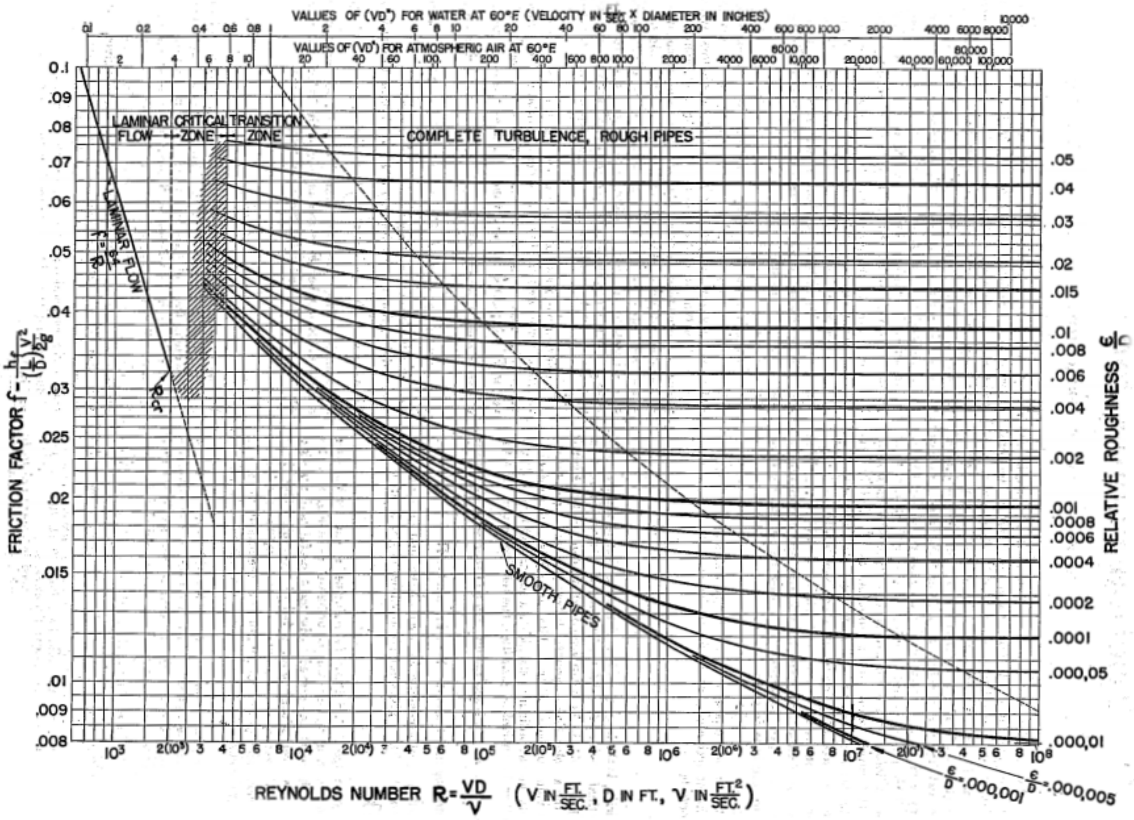


Figure 2.5.: *Moody diagram (Moody, 1944)*

2.4. Regulation stability

The power plants in the grid have to assure that the power consumed is equal to the power produced at all times. The power produced has to have a synchronized frequency of 50 Hz with a deviation that lasts for less than the duration given in table 2.1.

Frequency [Hz]	Voltage [pu]	Duration
45.0-47.5	0.90-1.05	>20 s
47.5-49.0	0.90-1.05	>30 min
49.0-52.0	0.90-1.05	Continuous
52.0-53.0	0.90-1.05	>30 min
53.0-55.0	0.90-1.05	>20 s
55.0-57.0	0.90-1.05	>10 s

Table 2.1.: *Combination of frequency and voltage which hydropower plants should operate without issues Statnett SF (2012)*

In a hydropower plant the hydraulic forces rotates a turbine which is connected to a generator that produces electricity to either a local grid or the main grid. Lets assume that the power production is equal to the power consumption at a given time. If the consumption is reduced than the surplus energy will cause the turbines to rotate faster, increasing the rotation of the turbine and the frequency of the power on the grid. If every power plant on the grid is unable to balance the power production to the power consumption then the grid will be unstable. A regulator monitors the turbines rotational speed and adjusts the water flow through the turbine to match the produced power to the consumed power on the grid (Nielsen, 1990).

To be able to regulate the flow of water fast enough to stabilize the grid the ratio between the the time constant of the conduits inertia, T_W, and the rotating masses inertia, T_a has to be higher then the required value given by Statnett SF (2012). The inertia ratio criteria ensures that the acceleration time of the turbine is higher than the inertia of the water masses in the conduit.

The time constant T_W defines the time needed to accelerate the water in the conduit from *0* to Q_0 under the influence of the head H as expressed in the following equation (Nielsen, 1990).

$$T_W = \frac{Q}{gH} \sum \frac{L}{A} \ [s] \tag{2.20}$$

The $\sum \frac{L}{A}$ in the equation is the sum of all the parts of the conduits length dividerd by their respective area from the nearest free water surface upstream of the turbine and to the turbine or valve which is closing.

If the time constant of conduits inertia is high, the deceleration forces during an intended reduction of discharge and power production can cause an unwanted pressure increase which will increase the power output (ibid.).

Frequency deviation on the grid will affect the rotation speed of the generator and turbine wheel. The mass of the rotating parts will have a stabilizing effect since the changes in rotational speed will be lower for systems with a higher rotating mass. The increased masses will increase the time it takes to accelerate or decelerate the turbine which will give the regulator or governor more time to counteract the deviation in the rotational speed. The time constant of the rotating masses inertia, T_a, can be defined as the acceleration time for the turbine and generator from an angular velocity of *0* to ω. The equation for T_a is expressed as followed (ibid.).

$$T_a = GD\frac{{\omega_0}^2}{4P_{max}}\ [s] \tag{2.21}$$

$$\omega_0 = \frac{N\pi}{30} \tag{2.22}$$

GD is the polar inertia of the generator and turbine, P_{max} is the highest power output of the turbine and ω_0 is the angular velocity. The angular velocity is determined by the rotations per minute of the turbine expressed as, N. An increase of T_a can be achieved by introducing an extra mass to the system, either through heavier turbine and generator or as a seperate flywheel. For large power plants the value of T_a is often in the area of 5-7 s (ibid.).

To achieve sufficient regulation stability the ratio between the time constant of the conduits inertia and the inertia of the rotating masses should be higher than 4, according to the criteria given by Statnett SF (2012).

$$\frac{T_a}{T_W} > 4 \tag{2.23}$$

Statnett SF (ibid.) criteria for stable hydropower production requires that the inertia ratio in Equation (2.23) is higher than 4. This will achieve a sufficient ratio between the rotating masses and the inertia of the conduit.

3 | Method

To determine if the hydropower plant fulfills the requirements for regulation stability the following criteria are given by Statnett SF (2012).

- The gain margin should be within the interval of $3 - 5$ dB
- The phase angle margin should be within the interval of $25° - 35°$
- The inertia ratio expressed in Equation (2.23) should be higher than 4
- The hydropower plant has to be designed to withstand a change in load from 100% on grid to 20% on an isolated grid
- The frequency deviation during a load change from 85% ± 10% has to be less than 0.6 % per percentage of load change
- The frequency deviation during a load change from 20% ± 10% has to be less than 0.3 % per percentage of load change
- The power plant should be able to operate a shutdown without exceeding the design pressure of the system

If an open or closed surge chamber is required the following criteria must also be satisfied.

- The design area of an open surge chamber has to exceed or be equal to the value of the Thoma criteria expressed in Equation (2.16)
- For closed surge chambers the volume of the air cushion has to be higher or equal to the criteria defined by Svee (1972) in Equation (2.17)

These criteria will be tested in the simulation program LVTrans to determine if a hydropower plant has sufficient regulation stability.

3.1. Method of Characteristics (MOC)

For analyzing transients in piping systems the method of characteristics (MOC) is the most widely used method. MOC has an analytical accuracy regardless of the grid size and in addition the calculations take a low amount of computational power (Svingen, 2005)

The derivation of the MOC in this section will be done on the basis of Svingen (ibid.) conference article on the use of LabView for simulating hydraulic piping systems. The

MOC can be derived by using the full 3D Navier-Stokes equations in cylindrical coordinates. The derivations leading to the 1D wave equation will be listed and the simplifications and assumptions that are used are shown, but the full derivation will not be listed.

The cylindrical and symmetrical effects of a pipe the 3D Navier-Stokes equation are reduced to 2D equations since all the variation in tangential direction will, because of symmetry, be zero.

There is assumed low compressibility, which is true for all liquid filled systems. The density with respects to pressure variation will then be of a constant value:

$$\frac{\partial \rho}{\partial p} = \frac{\rho}{\kappa} = \frac{1}{a} \tag{3.1}$$

Further the assumption of very low Mach numbers ($M^2 \ll 1$) is made. The assumption is valid for all liquid filled systems with exception of extremely flexible tubes. The assumption grants the convective terms to be disregarded.

The system can be assumed to be one dimensional if the pressure and velocity in the cross section of a pipe is averaged:

$$u = \frac{1}{\pi R^2} \int_0^R 2\pi R \nu_x dr \tag{3.2}$$

$$P = \frac{1}{\pi R^2} \int_0^R 2\pi R p dr \tag{3.3}$$

For systems where the characteristic length, L, to diameter ratio, D, is large the "long wavelength approximation" can be applied. The assumption is correct when the frequency of interest are lower than 63 % of the first radial fluid mode. For normal piping systems the first radial fluid mode will be several orders of magnitude higher than the modes of interest.

Excluding the low body forces compared to the other forces results in the 1 dimensional momentum and continuity equation. Also called the water hammer equations:

$$g\frac{\partial H}{\partial x} + \frac{\partial u}{\partial t} + \frac{f}{2D}u|u| = 0 \tag{3.4}$$

$$\frac{\partial H}{\partial t} + \frac{a^2}{g}\frac{\partial u}{\partial x} = 0 \tag{3.5}$$

Equation (3.4) and (3.5) are the ordinary 1D wave equations with a non linear dissipating term. Integrating along the characteristics lines of the equation and substituting the velocity with the flow will produce the characteristic solution of the water hammer equation that will be valid in the characteristic grid as seen in Figure 3.1:

$$C^+ : H_i = C_p - B_P Q_i + dyn \tag{3.6}$$

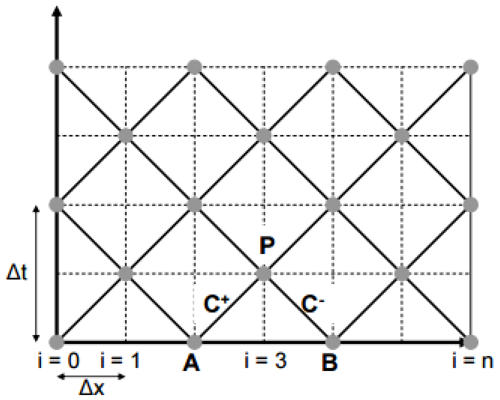


Figure 3.1.: *The characteristic grid, staggered type. Created by Svingen (2005)*

$$C^- : H_i = C_M + B_M Q_i + dyn \tag{3.7}$$

$$C_p = H_{i-1} + BQ_{i-1},\ B_p = B + R|Q_{i-1}| \tag{3.8}$$

$$C_M = H_{i+1} - BQ_{i-1},\ B_M = B + R|Q_{i+1}| \tag{3.9}$$

Where the physical properties of the fluid and pipeline, B, and the pipeline resistance, R, are substitute for the following values:

$$B = \frac{c}{gA},\ R = \frac{f\Delta x}{2gDA^2} \tag{3.10}$$

The dynamic dampening term is also included in the calculations, where:

$$dyn = \gamma(Q_{i-1} - Q_{i+1}),\ \gamma = \frac{\gamma f}{2\Delta x \rho g A} \tag{3.11}$$

The head, H, and discharge, Q, for every point can then be calculated by knowing the values at the previous time step (Svingen, 2005).

$$H_i = \frac{C_p B_M + C_M B_p}{B_p + B_M},\ Q_i = \frac{C_p - C_M}{B_p + B_M} \tag{3.12}$$

3.2. Achieving regulation stability

Achieving regulation stability is done by assuring that the power plant can change the flow of water to balance the power output to the power consumption on the grid. To ensure regulation stability the inertia ratio criteria has to be fulfilled. The inertia ratio consists of both the conduit and the rotating masses inertia. Changes in either of these will affect the inertia ratio. By disregarding the constant values and looking for which changes done to the system that will cause the inertia ratio to increase gives the following solutions which will help achieve the inertia ratio criteria.

- The following possibilities will decrease T_w and thus increase the inertia ratio
  - Reducing the length, L, by introduce a free water surface closer to the valve

  - Increasing the area of the conduit, A, lowering the maximum velocity of the water in the system.
  - Decreasing the maximum allowed discharge, Q_{max}, and thus decreasing the maximum velocity in the hydropower system
  - Increasing the head, H, will increase the forces acting on the water string which reduces the acceleration time of the conduit
- The following possibilities will increase T_a and thus increase the inertia ratio.
  - Increasing the polar inertia, GD
  - Decreasing the maximum allowed power output P_{max}

The length, L, which is present in Equation (2.20) for T_W and in Equation (2.11) for the increase of pressure due to water hammer, is described as the length from the valve or turbine to the nearest free water surface. A surge system is built to shorten this length and reducing the maximum pressure of the water hammer.

For hydropower plants with long conduits the inertia ratio criteria described in Equation (2.23) is especially hard to fulfill. A long distance between the turbine and the nearest free water surface causes a high water hammer pressure. For instance the small hydropower plant Usma, which will be examined in this paper, has a length from turbine to the basin of 5.5 km. As built, the power plant relies on closing the valve from full discharge to zero over a period of 150 seconds which is considered to be very slow. Increasing the closing time will help reduce the unwanted pressure increase from the water hammer, but the power plant becomes to slow to operate with regards to regulation stability. By introducing a free water surface to the system, the amount of water which has to be accelerated or decelerated can be chosen to fulfill the criteria of regulation stability which will allow for a reduced closing period of the valves (Guttormsen, 2006).

The maximum distance that the surge system can be placed from the valve or turbine can be calculated using Equation (2.20) where the length, L is the unknown. Assumptions and or design criteria can be used for the factors such as discharge, head and conduit area. To find T_a, common or known values for the turbine and generator can be used. The maximum length that the free water surface has to be placed can be found by inserting these factors in the Equation (2.23). If this length is shorter than the total conduit length then a surge system is not necessary. If the maximum length is longer, then the terrain and placement of the conduit has to be examined to find the optimal surge system and placement. Several surge system solutions already exists and will be examined in the following subsections.

3.2.1. Open surge chamber

Introducing a free water surface to the conduit can be done by constructing an open surge chamber that is connected to the system. The surge chamber construction has to be elevated high enough to contain the water rise due to upsurge and so that air entrainment during downsurge does not occur. The water level in the open surge chamber will be equal to the basin level during no discharge. The level will decrease with the headloss of the conduit during a discharge Q. The maximum upsurge of the chamber can be calculated with iteration and simulations or estimated ($\pm 10\%$) with Equation (2.12) (ibid.).

Introducing a surge chamber will help reduce the water hammer pressure, but it has a side effect of generating a mass oscillation in the system. The surge chamber has to be designed to dampen the mass oscillations over time. The Thoma criteria, seen in Equation (2.16), is a minimum area of the surge chamber needed to dampen the mass oscillations over time. A higher water surface area will reduce the maximum peak of the mass oscillations due to the increase in counterweight from the air pressure that is acting on the water surface. Different techniques to increase the area and reduce the surge chamber cost is exists:

When excavating in rock the tunnel may be driven with an inclination which increases the water surface area of the surge chamber. Using the topography is also a possibility to construct the surge chamber with an inclination while reducing the construction cost by not building a tower. Examining the different conduit designs while choosing the surge solution is important. Surge chambers may also be constructed to exceed the topography, by building concrete or steel constructions that will contain the water during operations. Creating or using basins which will behave like a large surge chamber is also possible.

In addition to reducing the length, L, from turbine to nearest free water surface, a free water surface can help alleviate air that will accumulate if there is a summit in the conduit. Air that accumulate in summits of a conduit will cause a reduced area of which the water can flow, which will increase the head loss, or cause a blockage of the water flow. A traditional placement of the conduit will construct the conduit with a slope and avoiding summits where air can accumulate. A surge chamber, either closed or open, placed in a summit will help alleviate the air accumulation by allowing the air to escape, essentially acting like an air pressure relief valve. The presence of a surge chamber may therefore allow the conduit design to have a summit without the risk of air accumulation.

3.2.2. Closed surge chamber

Due to constraints in the terrain and cost, an open surge chamber may not always be feasible. The development of cheaper excavating of inclined tunnels running straight from the intake to the power station opened the possibility to construct a surge chamber with an enclosed air cushion. With a closed surge chamber solution the distance from turbine to the free water surface can, in most cases, be considerable reduced compared to an open surge chamber (Svee, 1972).

A closed surge chamber can be excavated in rock or constructed in steel and connected to the conduit or penstock. Compressed air is introduced to the closed surge chamber after the conduit is filled with water. The compressed air will act as a cushion which will introduce a free water surface. By varying the pressure of the air the elevation of the free water surface can be set, unlike the open surge chamber where the free water surface will be the same as the energy line of the water.

Maintaining a sufficient pressure of the air pocket is important for the operation of the closed surge chamber. Two mechanism causes pressure loss of the air cushion. Firstly the naturally saturated water is exposed to the higher pressured air in the surge chamber. Due to diffusion, the higher pressured air will be dissolved in the water, decreasing the pressure of the air pocket. Secondly, air may leak through fractures in the rock mass. This loss occurs when the air pressure in the surge chamber exceeds the water pressure that is present in the fractures. The air pressure loss has to be monitored and compressed air has to be applied to counteract the air loss mechanisms (Goodall et al., 1988).

The necessary air cushion volume is defined, for short tunnels, by the governing stability requirements. For very long tunnels, the magnitude of the pressure rise due to water hammer effects will dictate the size of the air cushion (ibid.).

To calculate the cost of a closed surge chamber made in steel, Irgens (1999) gives equations (3.13) and (3.14) to calculate the resulting forces on a thin cylindrical tank as seen in Figure 3.2.

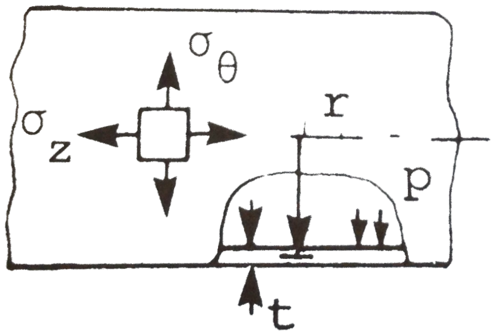


Figure 3.2.: *Resulting forces on a thin cylindrical tank with internal pressure p*

$$\sigma_\theta = \frac{r}{t}p \tag{3.13}$$

$$\sigma_z = \frac{r}{2t}p \tag{3.14}$$

From Irgens (ibid.) the internal pressure for a thin sphere has the same value as Equation (3.14). The thickness of the steel can be found by calculating the different resulting forces and checking if these exceed of are within the design yield strength of the steel.

3.2.3. Conduit design

Increased area

The conduit area can be increased to reduce the value of T_W in Equation (2.20). By increasing the area, the maximum velocity of the water in the system will be lowered, which can be seen in the continuity equation, $Q = Au$. By decreasing the maximum velocity the nominal acceleration time of the conduit will be lowered.

Reduced operating flow

T_W may also be reduced by decreasing the maximum operating flow, Q, that is allowed through the system by decreasing the maximum velocity of the water. The maximum operating flow is often set by the turbine chosen and the rating curve of the catchment. If the design flow criteria to achieve a sufficiently low T_W is lower than the optimal flow set by turbine and the rating curve the income potential of the power plant may decrease. The solution of reducing the maximum operating flow may be a valid solution, but the loss in income potential should be estimated and considered. The basin size for most of the small hydropower plants are so small that the a lower maximum water flow will increase the amount of water which will be lost over the spillway, which will reduce the income potential of the hydropower plant.

3.2.4. Other solutions

Turbine and generator

The inertia ratio in Equation (2.23) can be modified by increasing the time of inertia for the rotating masses in Equation (2.21). In the equation the frequency of the grid is constant and therefore a change in either the polar inertia, GD, or the maximum power output, P_{max} can be made. Comparing a change of the the two parameters, a decrease in the maximum power output may affect the economy of the power plant more than increasing the mass of the turbine and generator. The power output is also more commonly determined by the discharge curves of the catchment and not to increase the time constant for the rotating masses inertia. Increasing the polar inertia is on the other hand a relatively easy and cost efficient way to achieve a higher T_a.

Different projects have different turbines and generators. The inertia of the rotating masses for a small hydropower plant will be in the range of 1-2 seconds and often 1.2-1.5 seconds according to Svingen (2015).

The increased mass can also be added as its own rotating unit. A flywheel with the increased mass may be installed in the hydropower plant to increase T_a and will have the same effect as increasing the mass of the generator or turbine.

For small hydropower plants the work found in the guide of SWECO Norge (2010) can be used to determine which turbine will be optimal. By determening the net head, H, and the maximum flow, Q_{max} the optimal turbine may be found in Figure 3.3.

Determining the turbine parameters can be done with spreadsheets. In this paper the spreadsheet for a Francis runner which can be found in the LVTrans file system is used. The spreadsheet is made by Bjørnar Svingen.

Heating element

A power plant can be run on constant power output that is higher than the power need on the grid, the excess power can be used to heat production. By varying the power consumption of the heating element to match the excess power, the power plant can be run with constant discharge and power output. This method has been used in the early years of power production, and can still be a valid solution. The excess power could be used for any sources that can quickly increase or reduce the power usage to keep the demand of power equal to the production of power.

Hydropower plants are often in remote location so a heating element would often be hard to take advantage of. Using the excess power to make hydrogen could be a valid

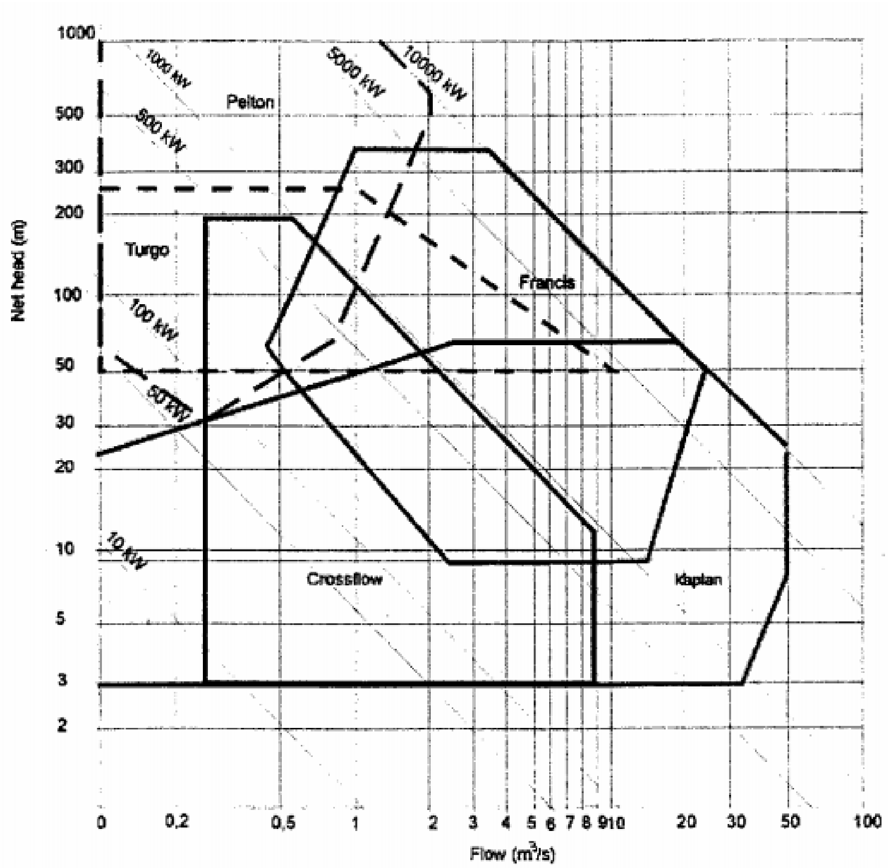


Figure 3.3.: *Example of turbine choices at different net head and flow (SWECO Norge, 2010)*

solution, which would allow for regulation stability for the hydropower plant as well as a product which could be used further. A hydrogen plant connected to a power plant may produce up to 100 ton/year/MW according to Yumurtaci and Bilgen (2004).

Proposing another modern solution to a heating element would be to have a super computer connected to the power plant providing regulatory stability while computing repetitive tasks which can be helpful for scientific purposes or as an additional income for the power plant. Example of tasks could be protein folding, heavy simulations or Bitcoin mining. This is assuming that the computer can be set to run with a varying power consumption. Activating and deactivating the processor cores to balance the power consumption to the power production. The possibilities involved in this solution may allow for an additional income for a power plant by selling computational power. This could be integrated with existing cloud services which sell computational power. The power company can choose to have their own servers, or give other companies the possibility in exchange for cheaper power or other deals that may be appropriate. The drawback of such a solution would be that the complexity of the hydropower plant is greatly increased. The super computer would also have a minimum power consumption that has to be met, reducing the maximum power that could be sold to the grid, but the remaining power will be improving the stability of the grid.

Responsive bypass valve

The following section is a potential solution to increase the regulatory stability of a hydropower plant when the demand for power is reduced.

Water hammer occurs when there is a change in flow through the system. If the discharge is not changed, then no pressure increase will occur. This can be achieved at the cost of water loss by connecting the wicket gate control to a bypass valve. If the demand for power is reduced, the governor will reduce the discharge through the turbine. If the bypass valve is opened as much as the turbine is closed then the system will not experience any change in flow, and will in effect have achieved regulation stability. This solution works for when the power consumption on the grid is decreasing and the hydropower plant has to reduced the power production. If the power consumption on the grid increases then more water has to go through the turbine, a responsive bypass valve would not be able to help achieve regulation stability unless there is a constant flow of water going through the responsive bypass valve.

Having a constant flow of water through the responsive bypass valve can help achieve regulation stability when the power consumption on the grid increases. If the power consumption on the grid increases more water has to go through the turbine, the flow from the bypass valve can then be redirected and go through the turbine. The drawback of this is the loss of water to ensure that the power plant can increase and decrease the flow of water through the turbine at will.

It is uncertain how much water has to be run through the bypass valve to achieve regulation stability. This will vary for the frequency deviation on the grid. A grid with high frequency deviation will demand a higher flow of water through the responsive bypass valve than a more stable grid with low frequency deviation.

3.3. LVTrans

LVTrans is an object-based simulation program that uses the LabView interface. The software is developed by dr.-ing Bjørnar Svingen from Rainpower. In LVTrans each part of the hydropower system is represented with nodes. Each node has its own icon, function and parameters and is placed in the worksheet and connected with pipes to compile complex systems. The analyzing method LVTrans uses is the method of characteristics. LVTrans can simulate both in real time and at higher speeds. During simulations each node can be accessed and data can be viewed in graph form or logged to be reviewed in other software. The timestep of the calculations can be modified, the default value is $0.1s$. In this paper a timestep of $0.01s$ is assumed to give a sufficiently low margin of error.

3.3.1. Nodes

The nodes used to simulate the hydropower plants in this paper are detailed in this section, only the values which were modified are included in this presentation.

Firstly a model of the hydropower plant has to be made in LVTrans. Each node in LVTrans has to be connected with a pipe segment, the parameters of the pipe node can be seen in table 3.4.

Name	Unit	Description
L	[m]	Length of pipe
D	[m]	Diameter of pipe
f	[-]	Friction factor (Moody)
a	[m/s]	Speed of sound in water
Z_0	[m]	Geodesic height of left part
Z_1	[m]	Geodesic height of right part

Figure 3.4.: *Pipe node*

The basin is represented with its own node seen in table 3.5.

Name	Unit	Description
H_0	[m]	Nominal geodesic height of water surface

Figure 3.5.: *Basin node*

A Pelton turbine node uses the parameters expressed in table 3.6.

Name	Unit	Description
Q_r	$[m^3/s]$	Rated discharge
H_r	[m]	Rated height
N_r	[rpm]	Rated rpm
T_r	[Nm]	Rated mechanical moment
E_r	[Nm]	Rated electrical moment
T_a	[s]	Time constant of the rotating masses inertia
Poles	[-]	Number of poles in generator, two times the pole pair

Figure 3.6.: *Pelton turbine node*

A turbine in LVTrans has to be connected to a PID governor, this node parameters are expressed in table 3.7.

Name	Unit	Description
P_r	[MW]	Rated power output
N_r	[rpm]	Rated rpm
$P_{n,grid}$	[-]	Proportionality constant, on grid
$T_{i,grid}$	[-]	Integral constant, on grid
$P_{n,isolated}$	[-]	Proportionality constant, on isolated grid
$T_{i,isolated}$	[-]	Integral constant, on isolated grid
Closing time	[s]	Closing time for turbine
SP_0	[MW]	Set point, nominal effect

Figure 3.7.: *PID governor node*

For the cases where a closed surge chamber is needed, this an air cushion chamber node is used as can be seen in table 3.8.

Name	**Unit**	**Description**
$P_{initial}$	[mwc]	Initial piezometric head (absolute)
$V_{initial}$	$[m^3]$	Initial air volume
$Liq_{initial\ elevation}$	[m]	Initial water surface elevation
A_w	$[m^2]$	Surface area of water

Figure 3.8.: *Air cushion chamber node*

3.3.2. LVTrans model

Data gathered for the cases has to be refined and made into inputs for the LVTrans model. The hydropower model is set up with the blank nodes. Starting from the basin node and working downstream each pipe segment is added. A new pipe segment will be added when the pressure classification of the pipe changes or a change in the inclination of the pipes. Between the pipe segments a connection node is added. If wanted, a connection node can be replaced with a T-connection node which will allow for insertion of an open or closed surge chamber. The surge chamber and T-connection has to be connected with a pipe segment. A turbine is added to the system, for systems with a Pelton turbine this can mark the end of the model, while a Francis turbine would have at least one pipe segment and a lower basin after the turbine node.

With the blank nodes added the system can be run. When LVTrans tries to load blank nodes it will create a text file with the the default input values for each node. These node parameters, which was previously discussed in Section 3.1, has to be edited with the values from the data gathered. When the values has been edited, the simulation has to be restarted for the changes to be set in place.

3.3.3. Surge chamber design

In LVTrans the initial volume and pressure of the surge chamber is chosen. The simulation will use these initial values in the calculations and over time will reach a steady state. When examining the power plant in LVTrans it is wanted that the initial volume and the steady state volume does not differentiate far from each other. To reduce the difference of the two volumes the initial pressure can be modified. The initial pressure is originally calculated to be the level of the intake basin and subtracting the initial level of the surge chamber and the head loss through the conduit from basin to surge chamber. If the initial volume and the steady state volume differentiate by a large margin, $> 10\%$, the initial pressure should be increased or decreased.

3.3.4. APF plot

A systems dynamic behavior can be analyzed by examining the responses while applying controlled disturbances to the system. A frequency analysis can be done by simulating a hydropower systems that is opening and closing the wicket gates in an increasing frequency while logging the amplitude and phase angle response on the system. These two plots combined makes up the Bode plot or also called an amplitude-phase-frequency plot (APF-plot) (Nielsen, 1990).

The APF plot can be used to determine if a power plant has a sufficient regulatory stability by looking at the phase- and gain-margin and cross-over frequency. The cross over frequency is the point on the amplitude graph where it crosses the 0 dB line, this is where the amplitude ratio is equal to 1. The APF-plot also shows the phase angle and amplitude over different frequencies, the phase angle θ is defined as: $\theta - 180$ when the gain is equal to $0dB$. The phase angle margin show how far above - 180° the phase curve is during the cross-over frequency. The gain margin is defined as the gain value when the phase angle, θ is equal to zero (ibid.). Sufficient stability is characterized by the phase margin being within the interval of 25° to 35° and the gain margin being within the interval of 3 dB to 5 dB according to Statnett SF (2012). Changes in the governors PID values will affect the APF plot. Statnett SF (ibid.) has therefore in addition to the phase- and gain-margin, also classifies the PID parameter values which is given in table the following table.

	Good quality	Mediocre quality	Bad quality
K_p	$K_p > 3$	$2<K_p<3$	$K_p<2$
T_i	$T_i<8$	$8<T_i<12$	$T_i>12$

Table 3.1.: *Classification of recommended PID values (Statnett SF, 2012)*

The amplitude-phase-frequency plot can be generated in LVTrans. This is done by changing the PID module type from PID NT to PID AFF Ramp, which has the function of generating an APF plot. From the APF plot the phase- and gain-margin can be reviewed.

Before generating a APF plot the PID has to be set to run on an isolated grid and with an open feedback loop. The phase- and gain-margin will be affected by the PID parameters chosen, P and T_i. After the APF plot is generated the phase- and gain-margin can be reviewed. If the values are not fulfilling the criteria set by Statnett SF (ibid.) the PID parameters has to be changed. Finding the right parameters is done by trial and error by figuring out how the phase- and gain-margin responded to changes in the parameters and tweaking them to achieve the criteria given by Statnett SF (ibid.). The following table shows the response on phase- and gain-margin when increasing the given parameter.

	Phase margin response	**Gain margin response**
P^+	-	-
T_i^+	+	+
V_{air}^+	-	-

Figure 3.9.: *Observed phase- and gain-margin effects on increasing parameters during simulations of Usma power plant*

In cases where changing the P and T_i factors does not achieve the criteria given by Statnett SF (ibid.) other factors can be changed, such as the length from turbine to the water surface of the surge chamber or the closing time of the turbine.

After the criteria for phase and gain margin is achieved the values of the APF plot can be saved and used to generate the APF plot in an external program, in this case Microsoft Excel.

3.3.5. Frequency deviation during load changes

The frequency deviation during load changes can be found by looking at the turbine node and the changes in RPM on the turbine during load changes. The scenarios of which the frequency deviation has to be examined are given by Statnett SF (ibid.) were previously mentioned in Section 3. The power plant is run through these scenarios while the turbine node is logging the RPM, which can be converted to the frequency, and the maximum frequency deviation can be found.

3.4. Cost comparison

The method of comparing the cost of achieving regulation stability is proposed to be done with the key financial ratio of cost of solution per kWh of produced power. By comparing with the key financial ratio the difference between regulation stability for small and large hydropower can more easily be compared.

3.5. Generalization of method

The work done in this paper is the basis of creating for the generalized method for achieving regulation stability which can be used for future hydropower plants. The choice of solution will be greatly affected by the variations in terrain, hydrology and tje design of hydropower plants. The generalization of achieving regulation stability is focused on small hydropower plants, but the principles are the same as for larger hydropower plants. The method should be used in accordance with cost estimates that are up to date, for example the cost estimate from NVE for small hydropower made by SWECO Norge AS (2010b). A version for larger hydropower plants also exists.

Determining which solution is optimal for a hydropower plant is dependent on the terrain and design choices of the hydropower plant. Through the research and writing of this paper the following guidelines for achieving regulation stability was found to be a general step by step guide for achieving regulation stability. All hydropower plants has the possibility to be stable, but the cost will greatly depend on terrain and hydrology of the project.

1. Gather in hydrological data and map of terrain
2. Outline the different routes for the conduit and determining the turbine type
3. Calculate the inertia ratio and check if criteria of inertia ratio > 4 is achieved. If this is not achieved the following solutions may increase the ratio, either one or a combination of several can be used .
    a) Reducing the length from turbine to nearest free water surface
    b) Increasing the conduit area
    c) Reducing maximum flow Q
    d) Increasing T_a
4. If changes were done, calculate the new inertia ratio, if the inertia ratio is still $<$ 4 change or add on more of the solutions expressed in step 3
5. Calculate the water hammer pressure increase in front of the turbine. Below is a list from most expensive to the cheapest pipe materials and their corresponding design pressures. The maximum water hammer pressure has to be lower than the

design pressure of the conduit, if not then the options in step 3a, 3b and 3c should be revisited

   a) Cast iron pipes for piezometric head $<$ 1000 mWC, high cost and not often used for piezometric head lower than 500 mWC (Brødrene Dahl AS, 2015)
   b) GPR pipes for piezometric head $<$320 mWC (ibid.)
   c) PE pipes for low piezometric head $<$ 200 mWC

6. Simulation of the power plant with the choices made can give more information on the dynamic of the power plant, this is especially recommended if a surge chamber is planned. Below is a list of values which can be found through simulation
   a) Maximum water hammer pressure
   b) Maximum and minimum water level of surge chamber
   c) Initial pressure of a closed surge chamber
   d) Necessary surface area and/or volume of surge chamber

Selecting which surge system is best for the hydropower plant in regards to 3a is detailed in the list below.

1. Calculate the maximum length from turbine to the water surface in the surge chamber with the inertia ratio expressed in Equation (2.23)
2. The conduit placement should be plotted into the map of the terrain. The maximum length should be marked and the possible surge chamber placements should be examined
3. Surge chambers placed in the summits of a conduit will allow air to escape without the need of a pressure release valve. By designing the conduit with a surge chamber in mind can allow a more unrestrained conduit profile and opens the possibility to construct a cheaper conduit
4. When making an assessment of an open surge chambers the following is important
   a) The water level in the open surge chamber during zero flow will be the same as the water level of the basin
   b) The water level of the open surge chamber when the flow is higher than zero is equal to the water level of the basin subtracted by the head loss in the conduit from basin to surge chamber.
   c) The Thoma criteria, expressed in Equation (2.13), gives the minimum surface area of an open surge chamber
      i. An inclined surge chamber will maximize the surface area of a given cross section

   d) A surge chamber will cause mass oscillation in the system, an estimate within $\pm 10\%$ of the maximum upsurge can be calculated with Equation (2.12). Simulations of the hydropower system can give more accurate results

5. When assessing a closed surge chamber the following is important
   a) The Svee criteria for minimum area and volume can be calculated with Equation (2.17) and (2.18), respectively
   b) The initial pressure can be estimated by subtracting the elevation of the surface level of the closed surge chamber and the head loss from basin to surge chamber from the elevation of the basin
   c) A closed surge chamber allows for conduit with a constant inclination, reducing the need for a high surge shaft
   d) A compressor and measurement equipment is needed to assure that the air pressure in the closed surge chamber is at appropriate levels
   e) The maintenance of a closed surge chamber is higher than that of an open surge chamber, which practically needs no maintenance

4 | Case studies

4.1. Usma Power plant, 9.98 MW

The power plant is built with a production of 9.98 MW. Usma is classified as a small hydropower plant <10 MW, and is therefore built without the criteria for regulation stability. In addition the power plant has the longest buried piped conduit in Norway, 5.5 km long. The first 4.2 km of the conduit have a slope of <1 % and the following penstock has a slope of 28 %. The buried pipes of Usma has a diameter of 1.4 meter.

The power plant was designed by Sweco Norge AS. The power plant is currently operational. Since the power plant is excepted from having regulation stability the power plant is operated slowly to avoid the problems of increased pressure from water hammer. Emergency shutdown procedure from full discharge takes about 150 seconds which was logged during a test for the project thesis of the author.

With the data collected from Appendix A the characteristics of Usma are calculated for the system as it was built.

The time constant of the rotating masses inertia, T_a, is calculated using Equation (2.21).

$$T_a = 48 \cdot 10^3 \frac{(\frac{500\pi}{30})^2}{4 \cdot 9.98 \cdot 10^6} \approx 3.3\ [s] \tag{4.1}$$

The time constant of the conduits inertia, T_W, is calculated using Equation (2.20) and the values from Appendix A.

$$T_W = \frac{4.4}{9.81 \cdot 286} \sum \frac{5500}{1.54} \approx 5.6\ [s] \tag{4.2}$$

The values from Equation (4.1) and (4.2) are inserted in the inertia ratio which is expressed in Equation (2.23):

$$\frac{3.3}{5.6} \approx 0.59 < 4 \tag{4.3}$$

which is less then the inertia ratio criteria recommended by Statnett SF (2012).

The Allievi constant expressed in Equation (**??**) can be calculated with by first calculating the reflection time of the water hammer. The speed of sound through the pipes, c, is assumed to be equal to the average speed of the whole system. The calculation of c is as follows:

$$c_{avrg} = \sum_{i=1}^{i=n} \frac{L_i \cdot c_i}{L_{tot}} \tag{4.4}$$

$$c_{avrg} = \frac{3372 \cdot 420 + 972 \cdot 440 + 300 \cdot 500 + 252 \cdot 530 + 335 \cdot 1018 + 122 \cdot 1044 + 147 \cdot 1067}{5500} = 500 \tag{4.5}$$

$$T_r = \frac{2 \cdot 5500}{500} = 22\ [s] \tag{4.6}$$

$$h_w = \frac{5.6}{22} = 0.25 < 1 \tag{4.7}$$

The Allievi constant does not fulfill the criteria of being greater than 1 is not fulfilled.

Using the criteria set in chapter 3, Usma does not fulfill the criteria of regulation stability as it is built today.

4.1.1. Achieving regulation stability

A possible solution to decrease T_W is with an open or closed surge chamber. By setting the criteria in Equation (2.23) to equal 4, and combining this with the T_a at Usma, found in Equation (4.1), the maximum length from turbine to the water surface of the surge chamber can be found.

$$L_{max} = \frac{T_a g H A}{4 Q_{max}} = \frac{3.3 \cdot 9.81 \cdot 286 \cdot 1.54}{4 \cdot 4.4} = 810\ [m] \tag{4.8}$$

An open surge chamber may be placed at Usma. Combining the terrain profile of Usma found in appendix A and the L_{max} calculated in Equation (4.8) the open surge chamber shaft has to be placed closer to the turbine than L_{max} and will be over 100 meters high. This solution is of course possible, but it can be argued to not be esthetically pleasing.

The Thoma criteria can be calculated using the values given from appendix A and assuming the Manning number is equal to 90. The Thoma criteria is calculated using Equation (2.16):

$$A_{Th} = \frac{90^2 \cdot 0.35^{\frac{4}{3}} \cdot 1.54}{g \cdot 2 \cdot 282.5} \approx 0.55\ [m^2] \tag{4.9}$$

For a closed surge chamber the necessary volume can be calculated using Equation (2.18) assuming the surge chamber is placed at the elevation of 340 m.a.s.l. the initial pressure of the chamber is set to 159.5.

$$V_0 = 1.4 \cdot 159.5 \cdot 0.55 \approx 124\ [m^3] \tag{4.10}$$

The conduit pipes close to the turbine has a designed piezometric head limit of 320 mWC. It is expected that changing the pipes to increase the design pressure will be too expensive. The changes done to Usma must therefore ensure that the maximum pressure for the pipes does not exceed the design pressure of the conduit as built.

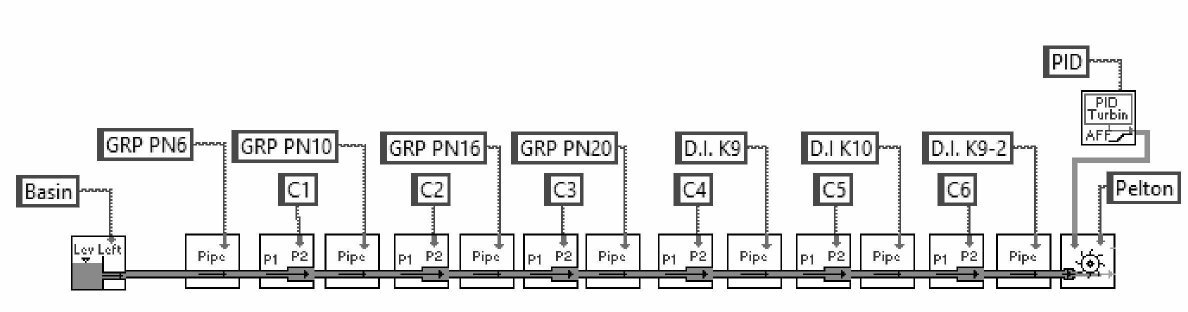


Figure 4.1.: *LVTrans model of Usma power plant, as built*

Using LVTrans a model of Usma power plant is made. The model can be seen in Figure 4.1.

In table 4.1 the pipe parameters used in the LVTrans model for Usma can be seen. These parameters are gathered from the case of Usma which can be found in appendix A.

Name	L $[m]$	D $[m]$	f $[-]$	ρ $[\frac{kg}{m^3}]$	a $[m/s]$	Area m^2	Z_0 $[m]$	Z_1 $[m]$
GRP PN6	3372	1.4	0.01	996	420	1.54	499	470
GRP PN10	972	1.4	0.01	996	440	1.54	470	440
GRP PN16	300	1.4	0.01	996	500	1.54	440	380
GRP PN20	252	1.4	0.01	996	530	1.54	380	340
D.I. K9-1	335	1.4	0.01	996	1018	1.54	340	268
D.I. K10	122	1.4	0.01	996	1044	1.54	268	238
D.I. K9-2	147	1.4	0.01	996	1067	1.54	238	217

Table 4.1.: *Pipe parameters for LVTrans model of Usma*

As well as the parameters for the PID turbine is shown in table 4.2

$P_r[MW]$	$N_r[RPM]$	$Sp_{Power}[MW]$	P_n^{grid}	T_{in}^{grid}	$T_{ramp}[s]$	$T_{close}[s]$	a	b
9.98	500	9.98	0.38	5.5	250	150	0.62	0.33

Table 4.2.: *PID Parameters for LVTrans model of Usma*

And lastly the turbine parameters used for the LVTrans model of Usma is shown in table 4.3.

$Q_r[\frac{m^3}{s}]$	$H_r[m]$	N_r	T_r	E_r	$T_a[s]$	Rm
4.11	272.2	500	190095	190095	3.3	0.05

η	$Poles$	Δ_R	$F_{nett}[Hz]$	$N_{needles}$	η_3	$q_{max}[\frac{m^3}{s}]$
0.906	12	0.6	50	6	0.81	1.5

Table 4.3.: *Turbine parameters for LVTrans model of Usma*

To increase the regulation stability at Usma, simulations with a closed surge chamber was done. As previously mentioned Usma power pants conduit has a design piezometric head of 320 mWC given the fact that changing the conduit is not wanted all situations at Usma power plant has to result in piezometric head increases that does not exceed 320 mWC.

Two alternative will be assessed for the surge chamber solution at Usma. The first assumes that the existing shutdown solutions which exists at Usma can be used during shutdown. The power plant activates the wicket gates, redirecting the water flow away from the turbine while a valve slowly (150 s) reduces the flow of water. If this solution is assumed to be used for Usma during shutdown procedures, then the designing maximum pressure the conduit will experience is the situation where the power planti s on 100 % on the grid and is disconnected and connected to the isolated grid with 20 % of the nominal power (Statnett SF, 2012). The other alternative will be to construct the power plant with the design condition of a full shutdown over an assumed closing time of 10 seconds.

Preliminary tests to find the correct dimensions of a closed surge chamber was done by inserting an air cushion surge chamber in the LVTrans model of Usma. The length from the turbine was set to 810 m, the initial volume to 124 m^3 and the initial piezometric head to 129 mWC. The Thoma volume is calculated to be 0.55 m^2, but this is increased to $\frac{1}{10}$ of the surge chamber volume to reduce the height of the closed surge chamber. The surface area of air too the chamber is set to 5 times the water surface area. Running the LVTrans model and looking at the steady state values of the piezometric head and volume gives 128 mWC and 125 m^3, respectively. The difference in pressure is due to friction loss and the difference in volume is sufficiently low, $< 10\%$.

With the aforementioned surge chamber in place the following situation is tested. The power plant is running on grid and producing 100 % of nominal power and then forced to stop. The pressure increase on the turbine node is logged, graphed and examined during this situation as can be seen in Figure 4.2. The maximum achieved piezometric head in this situation is close to 425 mWC, far higher than the design value of 320 mWC. As can be seen in the graph its a combination of the water hammer effects and the mass oscillations which causes the high increase in pressure. Simulations where the surge chamber has a greater volume and is located closer to the turbine could help reduce the pressure during the situation.

Reducing the length between the closed surge chamber and the turbine to 604 m by placing it in the connection between pipe segment GRP PN20 and D.I. K9. The volume is increased to 750 m^3, and the initial piezometric head is set to 160 mWC. The area of the surge chamber is still set to $\frac{1}{10}$ of the initial volume of the surge chamber and the surface area of the air to the chamber is set to 5 times the water surface area. The same situation is run with this closed surge chamber in placed and the pressure increase at the turbine is plotted in the following figure, Figure 4.3. As can be seen the mass oscillations and water hammer causes the piezometric head to increase higher than the pipes design condition of 320 mWC.

The closed surge chamber is now placed in the connection between pipe D.I. K9 and D.I. K10, 269 meters from the turbine. The initial volume is changed to 775 m^3 and the initial piezometric head is corrected to the new elevation and is set to 230 mWC. The result is plotted in Figure 4.5. The piezometric head increase in the situation will exceed the design criteria of the pipes of 320 mWC when the closing time is set to 10

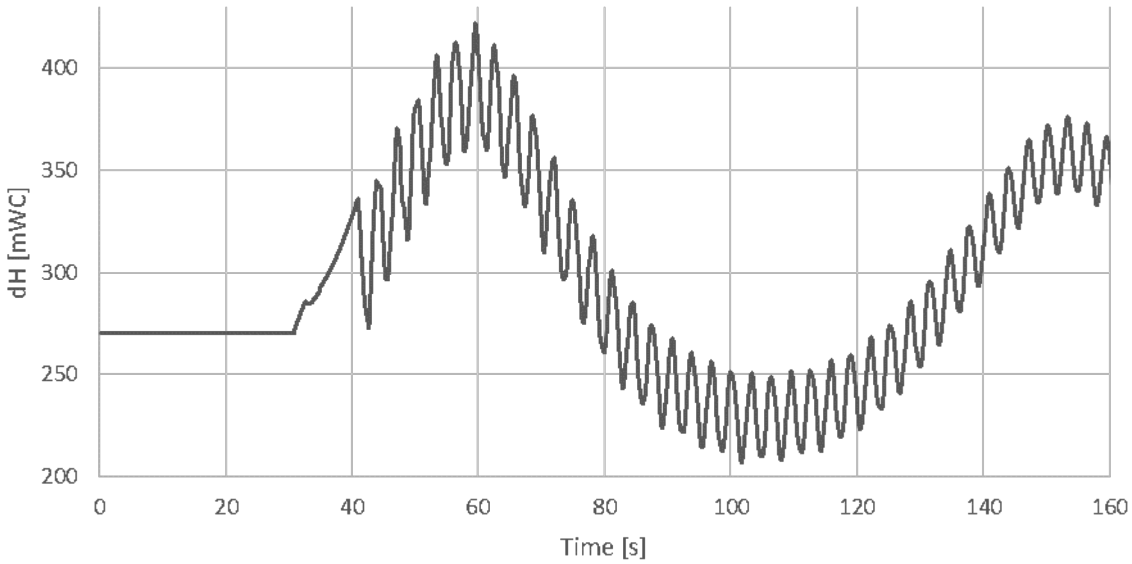


Figure 4.2.: *Shutdown of Usma from 100 % nominal power to 0 % with closed surge chamber air volume of 124 located 610 m from turbine*

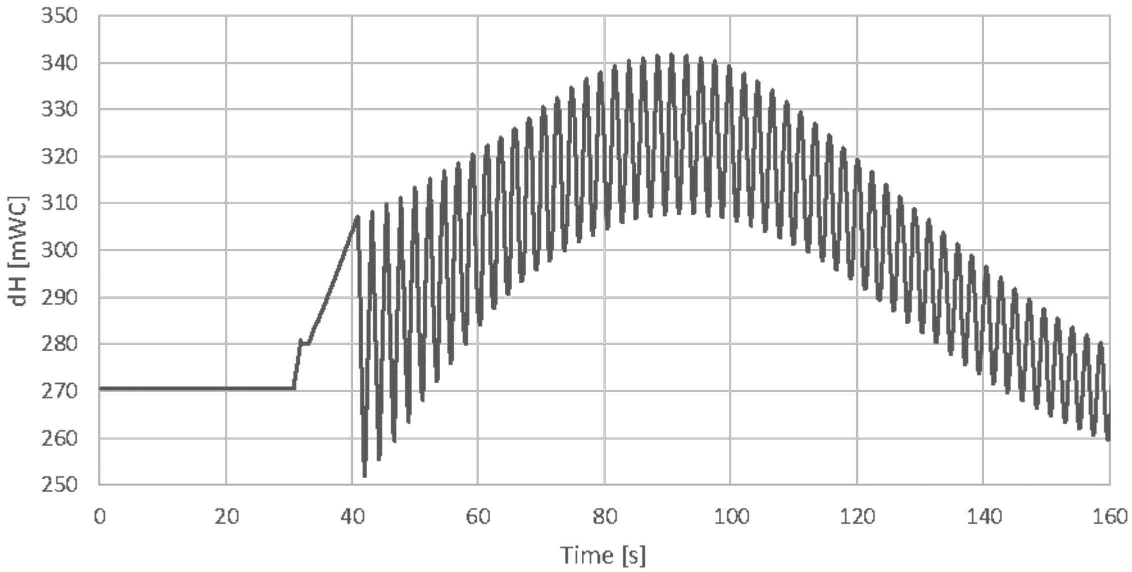


Figure 4.3.: *Shutdown of Usma from 100 % nominal power to 0 % with closed surge chamber air volume of 750 located 604 m from turbine*

seconds.

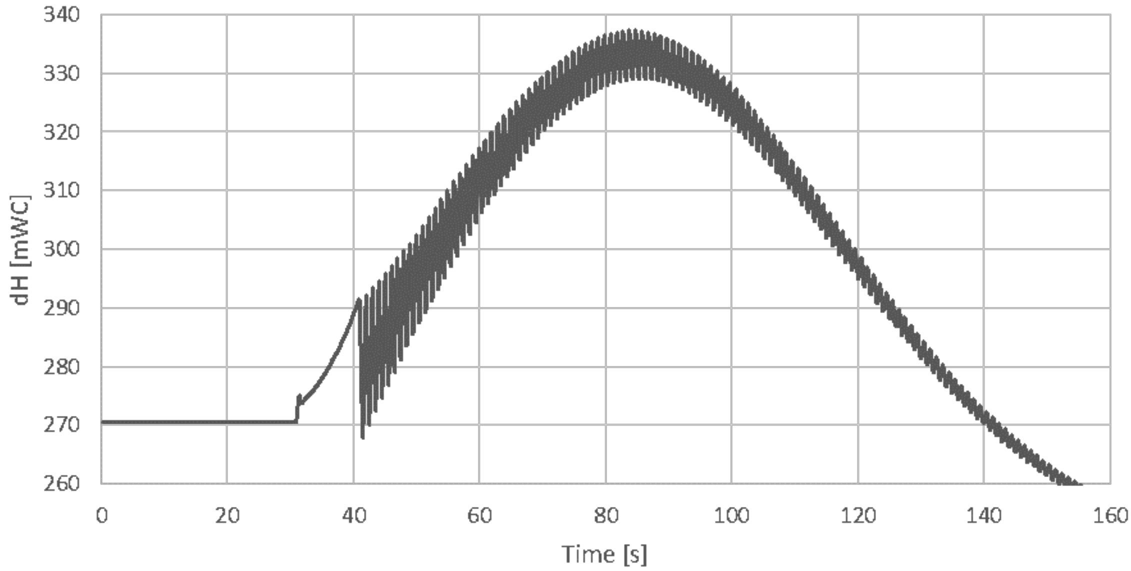


Figure 4.4.: *Shutdown of Usma from 100 % nominal power to 0 % with closed surge chamber air volume of 775 located 269 m from turbine*

If an assumption that a full shutdown will use the existing solution of activating the guide vanes and slowly reducing the flow of water then a lesser water hammer pressure will be the design criteria. Given this assumption the design criteria will be when the power plant is on 100 % on grid to 20 % on an isolated. The water hammer pressure increase for this situation is shown in Figure **??**.

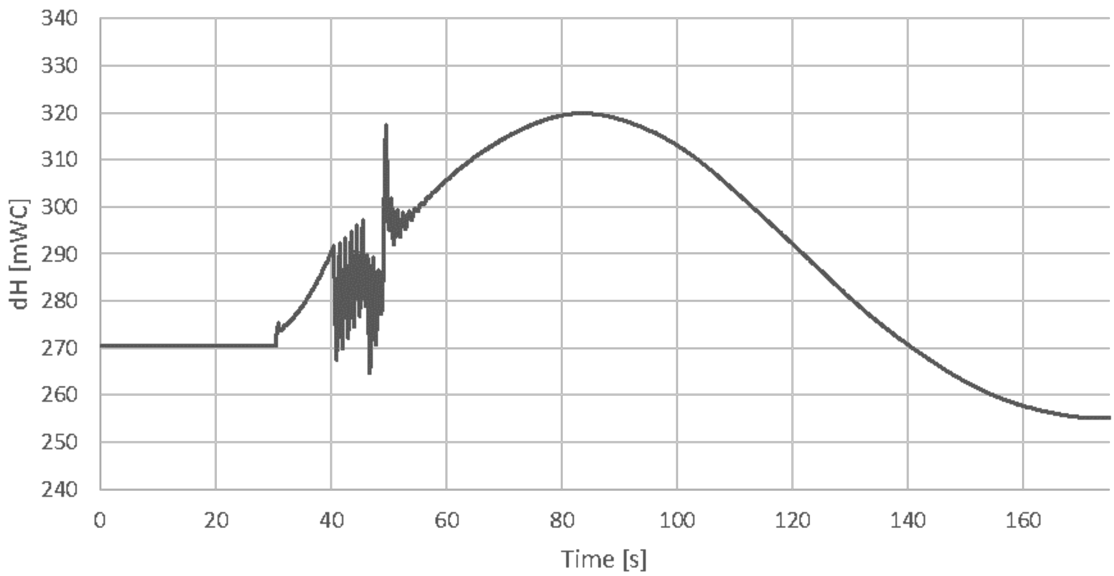


Figure 4.5.: *Pressure increase during load change from 100 % on grid to 20 % on isolated grid with 775 m^3 closed surge chamber at L=269 m*

With the aforementioned assumption and surge chamber the pressure increase is kept under design pressure of the conduit pipes. Now the PID governor can be examined and calibrated to fit the criteria given by Statnett SF (2012). Using the same simulation model with 775 m^3 closed surge chamber located 269 meters from the turbine an APF simulation is run. There are two PID parameters that is considered in this thesis, P and T_i. If the APF simulation gives a phase- and gain-margin that is not within the given criteria, the PID parameters are changed and a new simulation is run until the criteria is reached. The following APF-plot given in Figure 4.6 is found to fulfill the criteria set by Statnett SF (ibid.) when $P = 5.5$ and $T_i = 3$. The phase- and gain-margin are equal to 35° and 3.26, respectively

To confirm the previous results the pressure increase for the situation where the power plant is producing 100% nominal power on grid is changed to 20 % power on an isolated grid when the PID parameters are set to $P = 5.5$ and $T_i = 3$. As can be seen in Figure 4.7 the changes of the PID parameters has changed the maximum amplitude of the water hammer pressure during the situation that was simulated. This has increased the piezometric head that is observed to exceed the design criteria of the conduit pipes of 320 mWC.

A new change in position and size of the closed surge chamber is needed. Before this is done the water hammer pressure oscillation is observed to be jagged. Logging of the

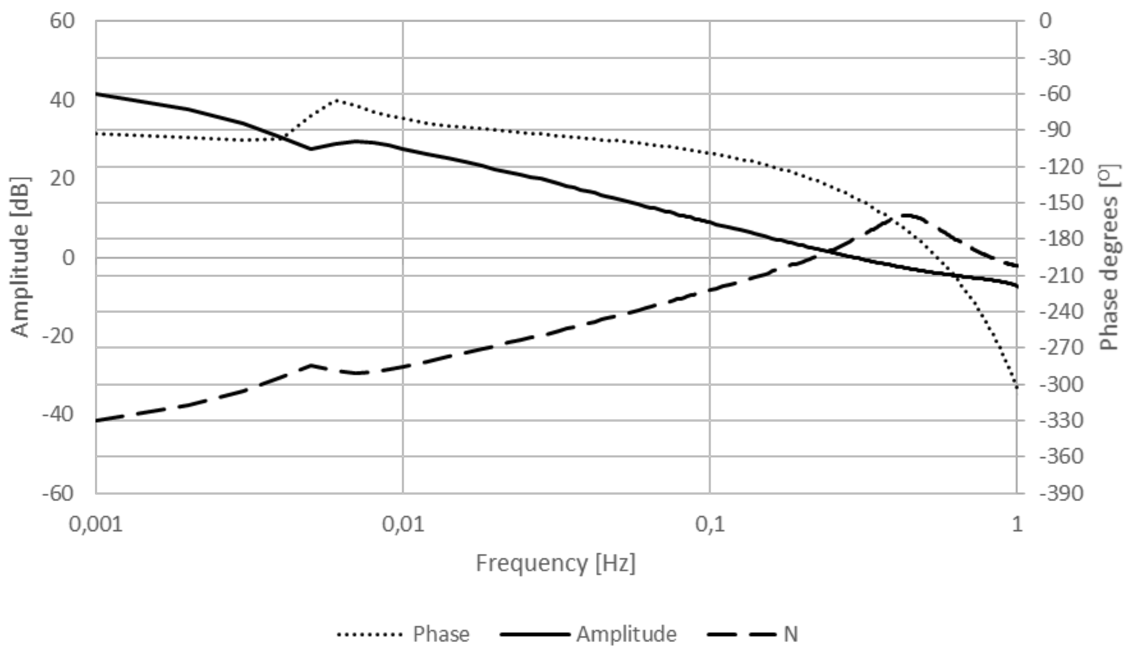


Figure 4.6.: *APF-plot of Usma with a closed surge chamber of 775* m^3 *with phase- and gain-margin equal to* 35° *and 3.26, respectively*

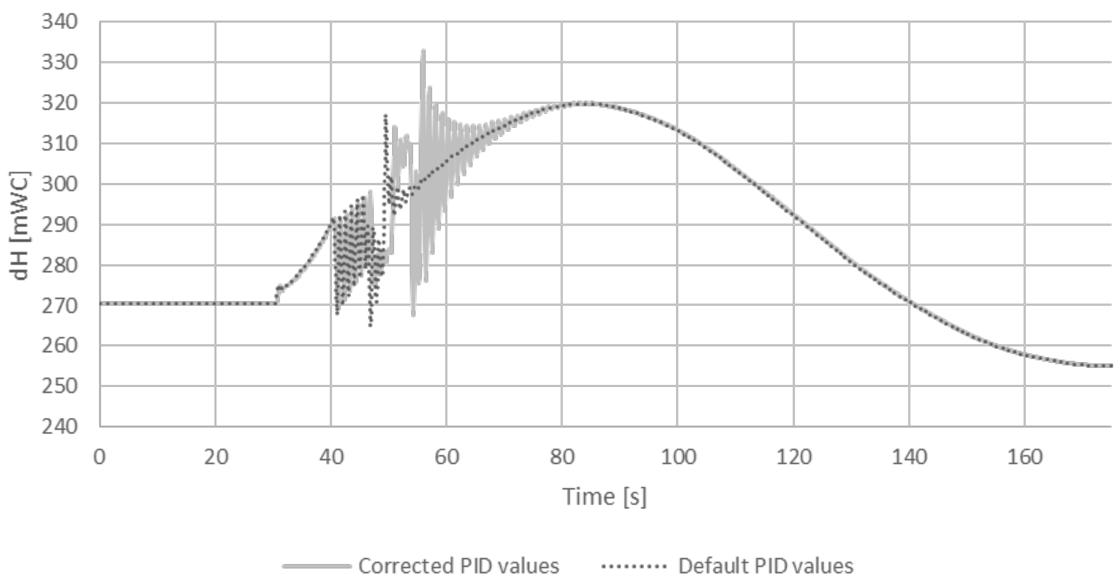


Figure 4.7.: *Pressure increase during load change from 100 % on grid to 20 % on isolated grid with 775* m^3 *closed surge chamber at L=269 m before and after correcting PID parameters*

turbines rotation per minutes, N, and the PID parameters changes on the discharge, κ, are logged and plotted in Figure 4.8 is done to understand what is happening. The results are plotted in Figure 4.8 and are used to interpret the water hammer oscillation:

When the load change is initiated the turbine spins faster and the PID governor tries to counteract this by reducing the discharge through the Pelton needles until it can not reduce any further, which can be seen as the kappa value is reduced to 0. The turbine will reduce in speed and when the turbine spins slower than 500 RPM the governor increases the discharge through the needles which will cause the first dip in the pressure increase which can be observed in Figure 4.7 at approximately $t = 50s$. This will increase the rotation speed of the turbine, reaching a higher rotation speed than 500 RPM. and the governor will again reduce the discharge which will cause the second water hammer pressure as can be seen in Figure 4.7 at $t = 55s$.

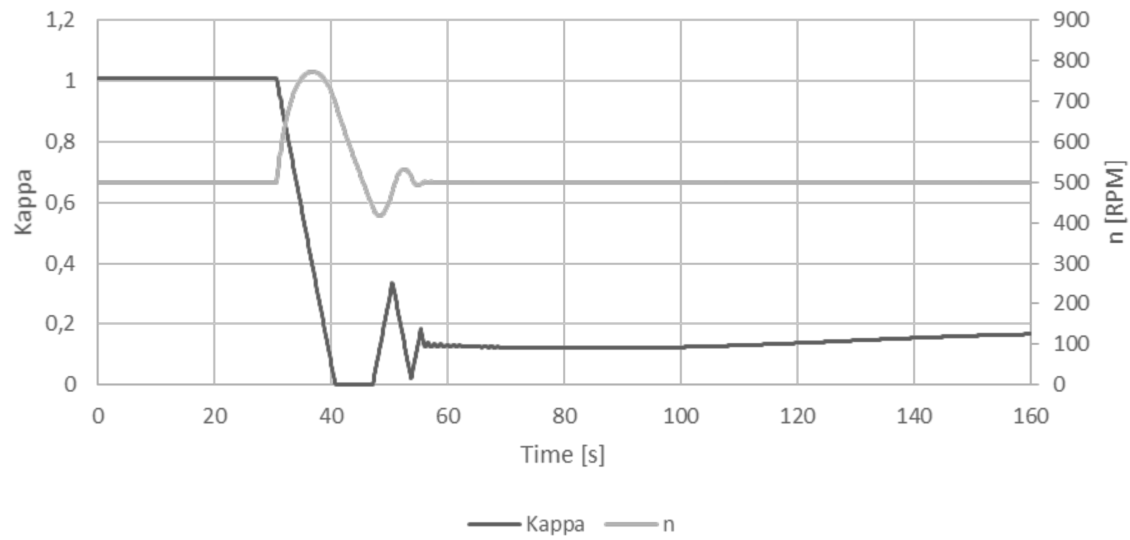


Figure 4.8.: *Relation between N and kappa during load change from 100 % on grid to 20 % on isolated grid with 775 m^3 closed surge chamber at L=269 m with corrected PID parameters*

As previously mentioned the surge chamber has to be placed at a reduced length from the turbine. This will decrease the water hammer effect, but will increase the mass oscillations and the need for a higher air volume of the closed surge chamber. To be on the conservative side the surge chamber is now placed at connection between pipe segment D.I. K10 and D.I. K9-2, which is 147 meters from the turbine. A conservative assumption is done by increasing the air volume to 1000 m^3, and the surface area is increased with the same increment as before, $\frac{1}{10}$ of the volume. Figure 4.9 shows the pressure at the turbine during a shutdown from 100 % nominal power.

The pressure is still higher than the maximum design pressure of the pipes, but using the same assumption of using the load change from 100 % on grid to 20 % on isolated grid as the design criteria gives the following results.

With this configuration an APF plot is made and the PID parameter values are again found using trial and error. The resulting APF plot in Figure 4.11 is found using $P = 10$ and $T_i = 10$. The phase- and gain-margin are equal to 34.4° and 3.3, respectively.

Testing for pressure increase during load change from 100 % on grid to 20 % on isolated

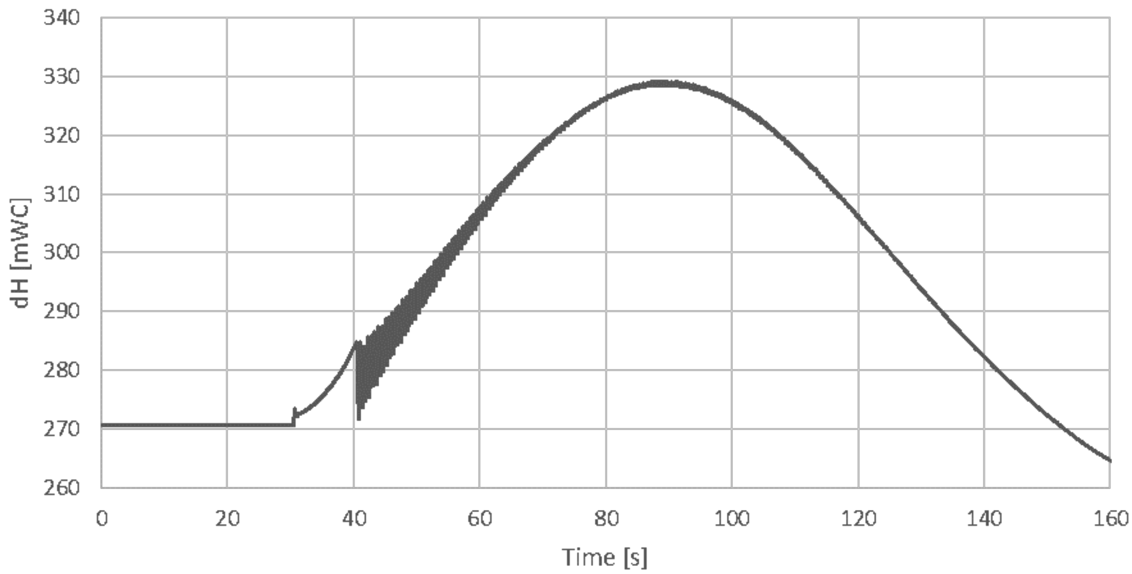


Figure 4.9.: *Shutdown of Usma from 100 % nominal power to 0 % with closed surge chamber air volume of 1000 located 147 m from turbine*

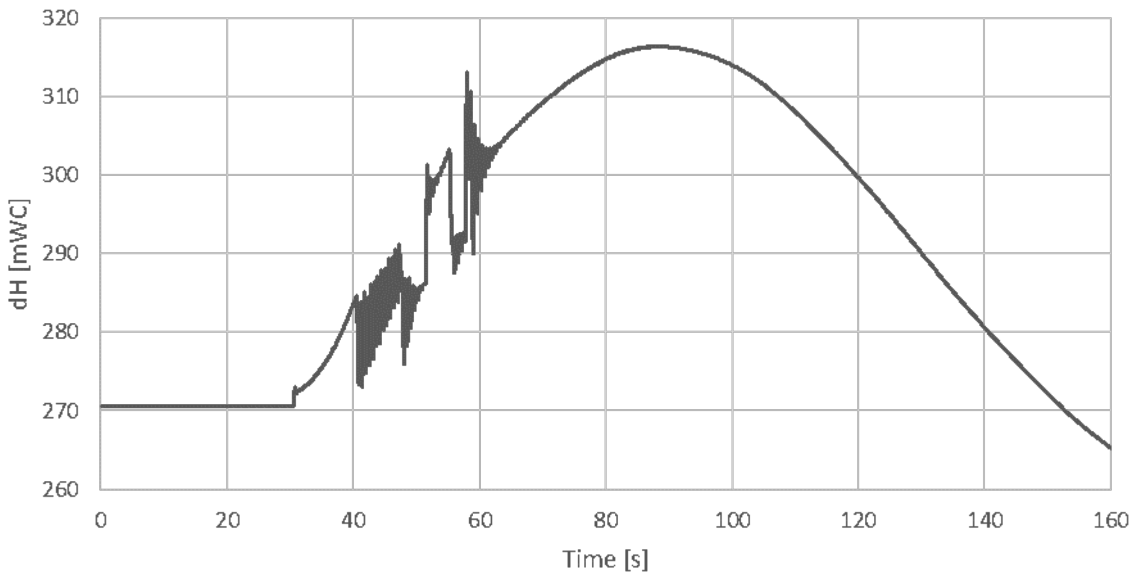


Figure 4.10.: *Pressure increase during load change from 100 % on grid to 20 % on isolated grid with 1000 m^3 closed surge chamber at L=147 m*

grid with the corrected PID values and comparing this with the old PID values from Figure 4.10 gives the following Figure 4.12. The changes in the PID values dos not affect the pressure increase so that the design condition is not fulfilled.

To further confirm the closed surge chamber design a shutdown from 100 % nominal power and from 20 % nominal power, on an isolated grid, is done while observing the

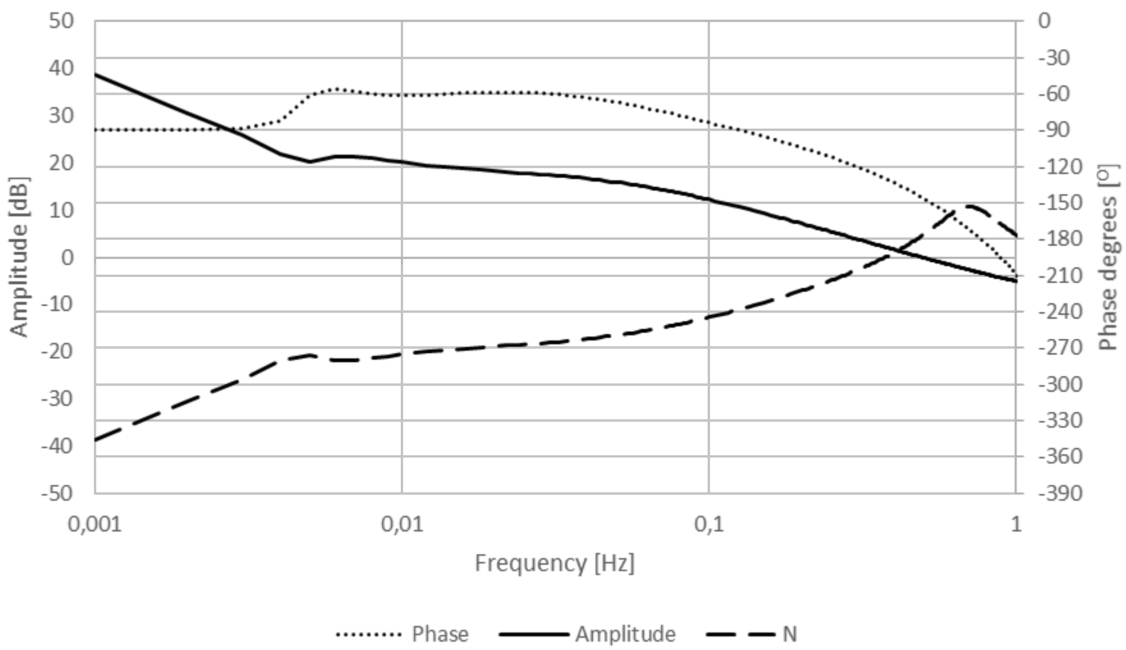


Figure 4.11.: *APF-plot of Usma with a closed surge chamber of 1000 m^3 with phase- and gain-margin equal to* 34.4° *and 3.3, respectively*

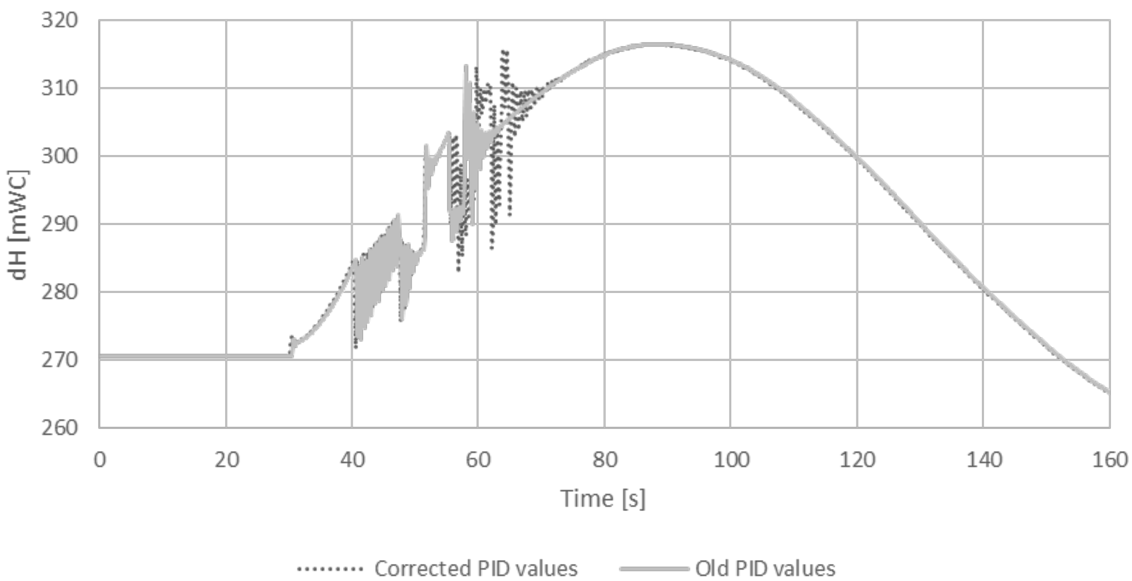


Figure 4.12.: *Pressure increase during load change from 100 % on grid to 20 % on isolated grid with 1000 m^3 closed surge chamber at L=147 m before and after correcting PID parameters*

water hammer pressure at the turbine. The closing time during shutdown is 10 seconds for both the cases, and will be initiated by the PID node in LVTrans. The two situations were logged and combined into Figure 4.13. The water hammer pressure in both cases are small. The mass oscillations are the major part of the pressure increase, but due to the huge size of the surge chamber they are below the pipes design piezometric head of 320 mWC.

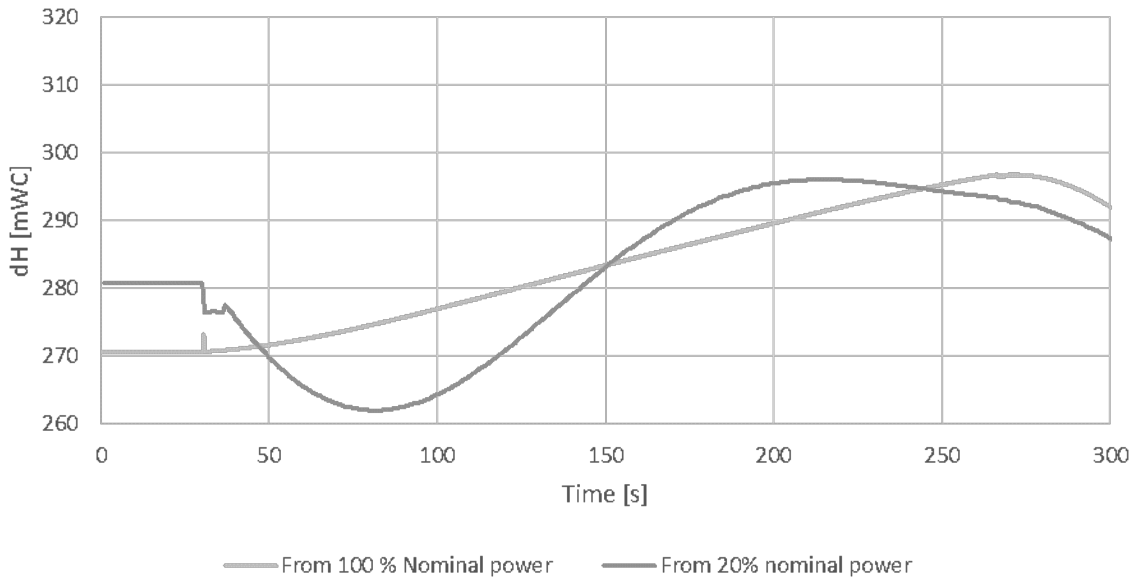


Figure 4.13.: *Shutdown from 100% and 20% nominal power on Usma with a closed surge chamber volume equal to 1000 m^3 located 147 m from turbine*

If the assumption of using 100 % on grid to 20 % on isolated grid is not valid then the surge chamber air volume has to be increased. A conservative volume of 1500 m^3 is tested. With the same assumptions on water surface area as before.

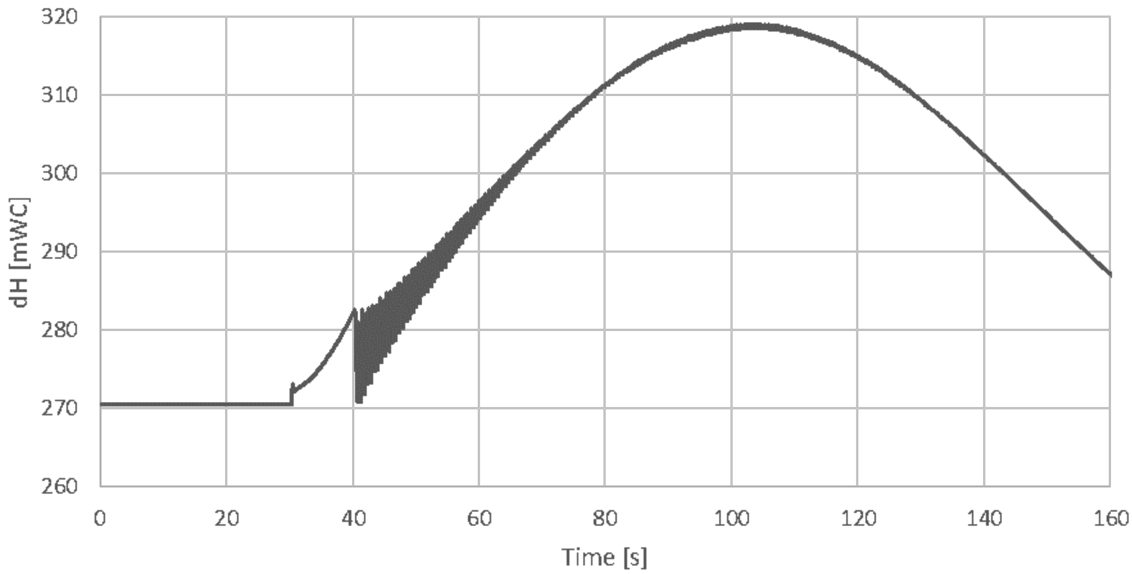


Figure 4.14.: *Shutdown of Usma from 100 % nominal power to 0 % with closed surge chamber air volume of 1500 located 147 m from turbine*

Which will result in a pressure increase within the design limits of the pipes in the conduit. An APF plot is made with the PID parameters: P = 10 and T_i = 10. The Phase- and gain-margin was equal to 32.4° and 3.15, respectively, as can be seen in Figure 4.15.

The frequency deviation criteria expressed in Section 3 has to be examined. This is tested for both the closed surge chamber alternatives, 1000 m^3 and 1500 m^3.

Figure 4.16 shows the frequency deviation for Usma with a 1000 m^3 closed surge chamber placed 147 meters from the turbine.

Figure 4.17 shows the frequency deviation for Usma with a 1500 m^3 closed surge chamber placed 147 meters from the turbine.

The frequency deviation for both alternatives at Usma with a 1000 m^3 and a 1500 m^3 closed surge chamber is 2 % when reducing the power output form 85 % to 75 % and 1% when reducing the power output from 20 % to 10 %. Both are below their respective criteria of 0.6 % and 0.3 % frequency deviation per percent of load change.

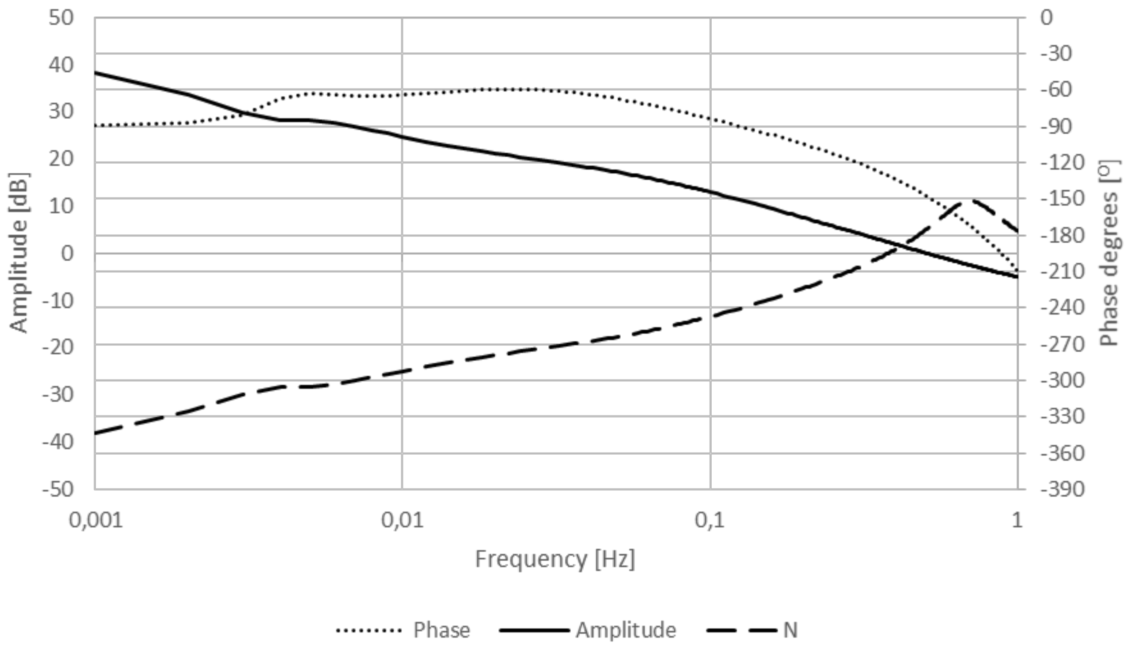


Figure 4.15.: *APF-plot of Usma with a closed surge chamber of 1500 m^3 with phase- and gain-margin equal to 32.4° and 3.15, respectively*

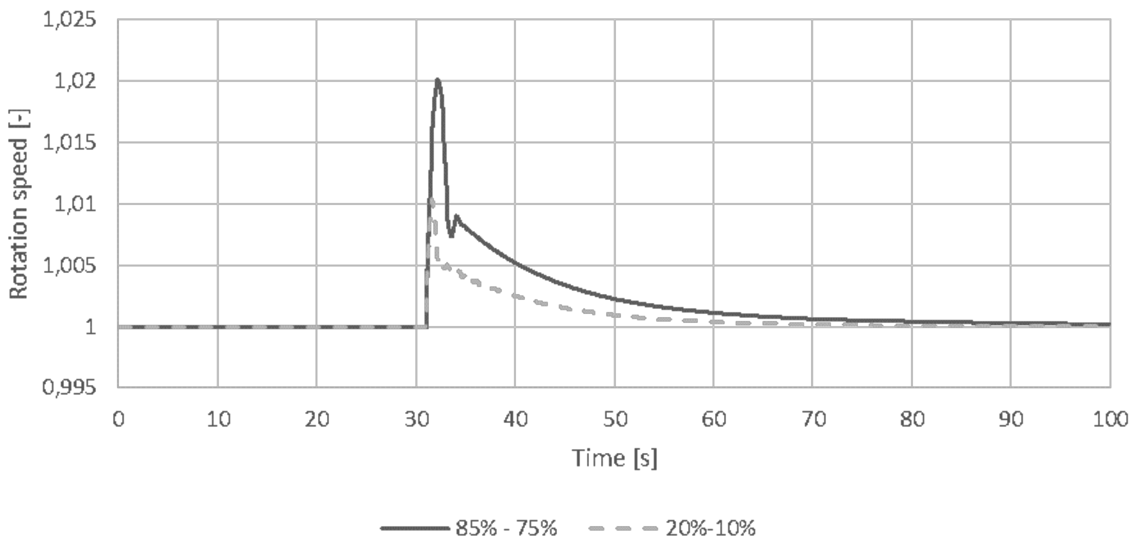


Figure 4.16.: *Frequency deviation of a reduction of power production for Usma with a 1000 m^3 closed surge chamber 147 meters from the turbine*

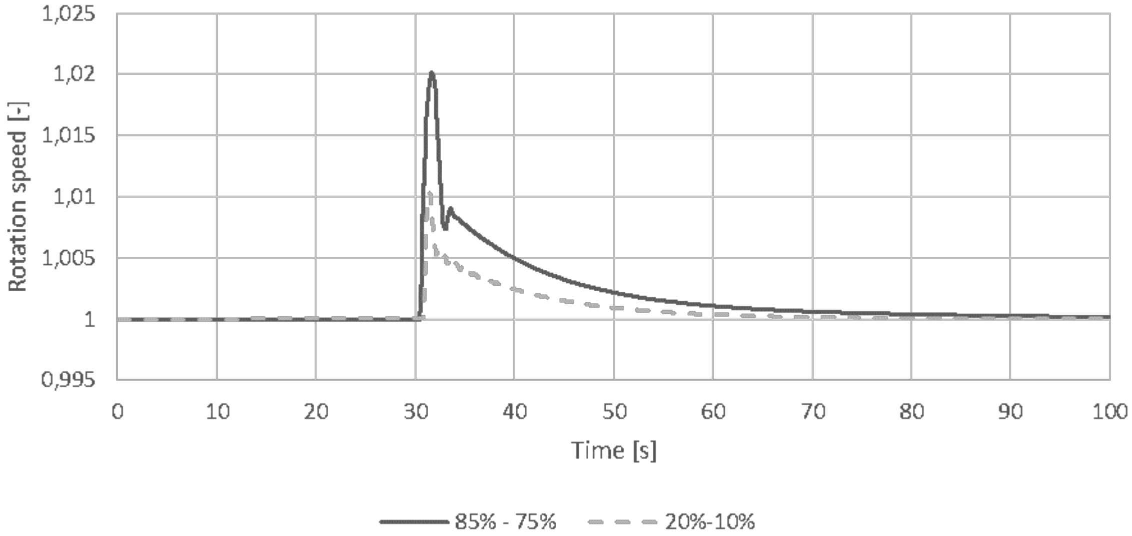


Figure 4.17.: *Frequency deviation of a reduction of power production for Usma with a 1500 m^3 closed surge chamber 147 meters from the turbine*

4.2. Cost analysis of Usma

Surge tanks made in steel is possible to obtain with piezometric head of 350 mWC and up to 190 m^3 (Quality Hydraulics, 2015). Combining several smaller surge tanks to obtain 1000 m^3 is a possibility for Usma where the volume too large for one tank to be sufficient. A single tank can be built at the construction site. The cost of such a construction is examined below.

The maximum piezometric head for the surge chamber is found to be less than 310 mWC. The internal area of the surge chamber is set to 100 m^2 and the internal height of the structure to 12 meters.

The surge chamber will be constructed as a 12 meter cylindrical structure with a half sphere on each end.

Calculating the internal piezometric head in the tank with $P_{max} = 310\ mWC$:

$$p = \rho_w g P_{max} = 1000 \cdot 9.81 \cdot 310 \frac{1}{1000^2} = 3.04\ [\frac{N}{mm^2}] \tag{4.11}$$

From Norsk Stål (2015a) product catalog a fitting steel plate is found by calculating σ_ϕ for different thicknesses and checking if this is less than the design strength of the steel plate. A thickness of 25 mm was sufficient when using the product Hot Rolled plate Weldox 700E.

$$\sigma_\phi = \frac{5642}{25} 3.04 = 686.3\ [\frac{N}{mm^2}] \tag{4.12}$$

$$\sigma_z = \frac{5642}{2 \cdot 25} 3.04 = 343.2\ [\frac{N}{mm^2}] \tag{4.13}$$

The steel volume can then be found by calculating the cylindrical volume and the volume of the two half spheres.

$$V_{cylinder} = ((5641 + 25)^2 - 5641^2)\pi 12000 \frac{1}{1000^3} = 10.7\ [m^3] \tag{4.14}$$

$$V_{sphere} = ((5641 + 25)^3 - 5641^3)\frac{4\pi}{3}\frac{1}{1000^3} = 10.0\ [m^3] \tag{4.15}$$

The density of steel is equal to 7800 $\frac{kg}{m^3}$ and the cost of steel is given by Norsk Stål (ibid.) to be 21.1 $\frac{NOK}{kg}$ for the given product. This is used to calculate the material cost for the closed surge chamber.

$$Cost = (10.7 + 10.0)7800 \cdot 21.1 = 3.4\ [10^6\ NOK] \tag{4.16}$$

In addition to the closed surge chamber construction an air compressor has to be installed to ensure that the pressure is at the intended level. A compressor with 500 psi and 22 $\frac{m^3}{min}$ can be in the price range of 0.1 million NOK. The necessary measurement equipment is estimated to cost 0.05 million (Suzhou Yuda Compressor Co., 2015).

It is also possible to rent a compressor, a request was sent to Atlas Copco for a compressor which could be fitted at Usma. A 24 bar compressor would cost 9 000 NOK per day, excluding diesel cost, plus an additional cost of 25 000 in transport. A 26 bar compressor could cost twice as much. The request and respond can be seen in appendix B. Depending on the need to pressurize the surge tank renting a compressor may be a valid solution for the long run. A rented compressor will increase the downtime during a loss in pressure, but removes the need for maintenance of the compressor. Air pressure loss can be considered to only be dissovled by diffusion and not air loss through the steel tank.

The surge chamber has to be designed and built. An estimate to the designing cost for steel constructions is to double the cost of the materials needed. In addition a 15 % cost will be added as unforeseen cost on top of the cost of materials, design and construction. In addition to the calculations done above, the cost estimate of a surge chamber of 1500 m^3 is calculated. The surge chamber will be as high, but with an area of 150 m^2. The same equations are used to calculate the cost, but with an increased diameter of the surge chamber. Table 4.4 gives the total estimated cost of a surge chamber of 1000 m^3 and 1500 m^3 for Usma.

	Cost [10^6 NOK] V=1000m^3	Cost [10^6 NOK] V=1500 m^3
Steel cost	3.40	4.63
Compressor and measurement equipment	0.15	0.15
Sum	3.55	4.78
Design and construction	3.40	4.63
Unforeseen cost	1.39	1.41
Total cost	8.34	10.82

Table 4.4.: *Cost of a 1000 m^3 and 1500 m^3 closed surge chamber in steel for Usma*

The cost of a surge tank is roughly estimated to be 8.3 million. Which does not account for the maintenance cost over the lifetime of the power plant. This cost is equal to 5% of Usmas total cost when it was built, 159 million NOK . Increasing the cost of Usma from 4.20 $\frac{NOK}{kWh}$ to 4.40 $\frac{NOK}{kWh}$ (Småkraftforeninga, 2014) for the 1000 m^3 surge chamber alternative with the use of existing shutdown procedures and 4.47 $\frac{NOK}{kWh}$ for a surge chamber with 1500 m^3 which can shutdown the power plant in 10 seconds. An increase of 0.2 - 0.3 $\frac{NOK}{kWh}$ will be the cost of achieving regulation stability for Usma, depending on the requirements which will be set for the power plant.

A responsive bypass valve can also be a solution valid for Usma. If the responsive bypass valve only is put in to maintain the regulation stability for lowering the flow through the turbine then a relatively small amount of water will be lost if the responsive bypass valve is set to reduce the flow of water slowly to avoid the increased pressure from water hammer. The existing Usma power plants regulates the power plant from 100 % to zero over a period of 240 seconds, the responsive bypass valve will have to shutdown as slow or slower than this. To calculate an estimate of the amount of water lost if the power plant is regulated from 100 % nominal power to 20 % nominal power and the responsive bypass valve is set to slowly close over a period of 240 seconds.

$$V_{loss} = \frac{\Delta Q \cdot T_{valve}}{2} = \frac{4.4 \cdot 80\% \cdot 240}{2} = 422 \; [\frac{m^3}{s}] \tag{4.17}$$

The power plant can produce 9.98 MW with 4.4 $\frac{m^3}{s}$. The power plant can be run for 96 seconds with 422 m^3 water available. This results in a power production of 266 kWh of production loss. With a power price of 0.3 $\frac{NOK}{kWh}$ this will result in a loss of 80 NOK for each load reduction from 100 % to 20 %.

If the responsive bypass valve is designed to grant a full regulation stability then there has to be a flow of water through the bypass valve at all times. It is not known how much water that has to be available at any given time to account for the changes in the grid frequency, but a conservative estimation of 10 % of maximum flow should be able to counteract some of the frequency changes. By having a 10 % of Q_{max} not flowing through the turbine the water is wasted for power production. For a situation where the power plant is running with full regulation stability for an hour the water loss can be estimated.

$$V_{loss} = \Delta Q \cdot 60^2 = 4.4 \cdot 10\% \cdot 60^2 = 1584 \; [\frac{m^3}{h}] \tag{4.18}$$

The water loss would have been enough to run the power plant for 360 seconds which results in a power production of 998 kWh. which will result in a loss of 300 NOK for every hour the plant is operated with regulation stability. With a yearly production of 38 GWh, Usma is operational for 3800 hours a year. The cost of regulation stability can therefore be assumed to be 1.14 million NOK each year. This assumes that the power plant is required to have regulation stability at any time. If the small hydropower plants are only required to provide stability to the grid during the worst periods: May, June, July and August as seen in Figure 1.1 then the number of hours the responsive bypass valve is operational will be reduced, and the loss of water and income is reduced.

4.3. Storvatnet, 1.4 MW

Storvatnet has received its license from NVE (2012). Although the power plant is not yet built, the terrain of the power plant makes it interesting when considering other positive effects when fulfilling the requirements for regulation stability.

The project is owned by Albert Collett ANS and is located in Nord-Trøndelag in Norway. The conduit of Storvatnet starts at the intake at Storvassdammen (111 m.a.s.l.), passes Damtjønna (117 m.a.s.l.) and ends with the outlet at Liavatnet (90 m.a.s.l.). The slope of the conduit is fairly small approximately 0.4 % since it passes the lake Damtjønna.

With data collected from the license application that is approved by NVE, the characteristics of Storvatnet can be calculated.

To examine Storvatnet further an LVTrans model is set up. The license application published by NVE (ibid.), is the main source of the following parameters. The license application did not include a detailed description of the conduit and turbine type. Some assumptions were therefore made to complete the model.

Name	L $[m]$	D $[m]$	f $[-]$	ρ $[\frac{kg}{m^3}]$	a $[m/s]$	Area m^2	Z_0 $[m]$	Z_1 $[m]$
P-1	600	1.8	0.01	1000	500	2.54	107.5	105
P-2	70	1.8	0.01	1000	500	2.54	105	87
P-3	15	1.8	0.01	1000	500	2.54	87	87

Table 4.5.: *Pipe parameters for LVTrans model of Storvatnet*

The turbine choice is done by using the figure given in NVEs guide for small hydropower plants. The net head at Storvatnet is 21 meters and the maximum flow is 8 $\frac{m^3}{s}$ according to the license application from NVE (ibid.).

The rated head of the turbine can be found with the Darcy-Weisbach equation. Inserting the values set from table 4.5 into Equation (2.19) gives the following results.

$$H_f = 0.01 \cdot \frac{675 \cdot 8^2}{2 \cdot 1.8 \cdot 9.81 \cdot 2.54^2} = 1.89\ [m] \tag{4.19}$$

$$H_r = 21 - 1.89 = 19.11\ [m] \tag{4.20}$$

With the rated head, H_r and maximum flow, Q_{max} the Figure **??** can be used to determine that a Francis runner can be used. The parameters for the Francis runner is unknown, finding them can be done with an excel document which is found in the LVTrans program folder. The spreadsheet is created by Bjørnar Svingen whom also was contacted to help with the results. The spreadsheet results showed that 14 pole pairs are needed to achieve a β angle between 13 and 21. Bjørnar Svingen was contacted and informed that the turbine of choice would be a Kaplan or a bulb turbine and not a Francis due to the low head and high water flow. Both of these two types are not possible to simulate with LVTrans so the recommendation was to simulate either 2-4 Francis turbines or 1 Francis turbine with non optimal β angle and a normal rotational speed. The latter was chosen and the rotational speed is set to 500 RPM resulting in the following parameters which can be seen in table 4.6. The email correspondence resulting in this decision can be seen in appendix D.

$Q_r[\frac{m^3}{s}]$	$H_r[m]$	$a_1[deg]$	$\beta_1[deg]$	$r_1[m]$	$r_2[m]$
8	19.11	62.8	86.8	0.270	0.285

T_a [s]	η_r	$Poles$	Δ_R	$F_{nett}[Hz]$	N_r
13	0.95	12	0.785	50	500

Table 4.6.: *Turbine parameters for LVTrans model of Storvatnet*

A terrain map of Storvatnet was included in the license application for Storvatnet (NVE, 2012). This can be found in appendix C. The parameters which were used were found in the license application sent to NVE (ibid.).

The time constant of the conduits inertia, T_W, is calculated using Equation (2.20) and the values from the license application (ibid.).

$$T_W = \frac{8}{9.81 \cdot 21} \sum \frac{675}{2.54} = 10.3\ [s] \tag{4.21}$$

The values from Equation (4.21) and the value of T_a is inserted in the inertia ratio which is expressed in Equation (2.23).

$$\frac{13}{10.3} \approx 1.26 < 4 \tag{4.22}$$

which is less then the inertia ratio criteria recommended by Statnett SF (2012)

The Allievi constant criteria also has to be checked. The speed of sound is assumed to be in the same area as the previous case study of Usma and will be set to 500 $\frac{m}{s}$

$$T_r = \frac{2 \cdot 675}{500} \approx 13.6\ [s] \tag{4.23}$$

$$h_w = \frac{10.3}{1.5} \approx 3.8 > 1 \tag{4.24}$$

The Allievi constant criteria is fulfilled. Since the criteria is independent of changes in the values of L, an open or closed surge chamber can be added to the conduit without affecting the Allievi constant.

4.3.1. Achieving regulation stability

In Equation (4.22) the inertia ratio at Storvatnet is calculated to be less than 4 if no surge chamber is installed. If the power plant is to be build with regulation stability then something has to be done to increase this ratio.

Increasing the area of the conduit is a possible solution. By solving the inertia ratio with the conduit area as an unknown the necessary conduit area is found.

$$A = \frac{8 \cdot 675 \cdot 4}{13 \cdot 9.81 \cdot 21} = 8.1\ [m^2] \tag{4.25}$$

Increasing the area from 2.54 to 8.1 m^2 can help achieve the required inertia ratio for Storvatnet. An area of 8.1 m^2 will need a minimum diameter of:

$$D = 2\sqrt{\frac{8.1}{\pi}} = 3.21\ [m] \tag{4.26}$$

A pipe with a diameter of 3.21 is possible, but will often exceed the cost of making a larger tunnel (SWECO Norge AS, 2010b). An LVTrans model with the minimum area of a tunnel, 12 m^2 will be used to simulate this option. LVTrans only operates with circular pipes, so the necessary diameter of the tunnel, if it was constructed circular will be:

$$D = 2\sqrt{\frac{12}{\pi}} = 3.9\ [m] \tag{4.27}$$

With this conduit area a shutdown when the flow is equal to $Q_{max} = 8\ m^3$. The pressure in front of the turbine is logged and shown in Figure 4.18.

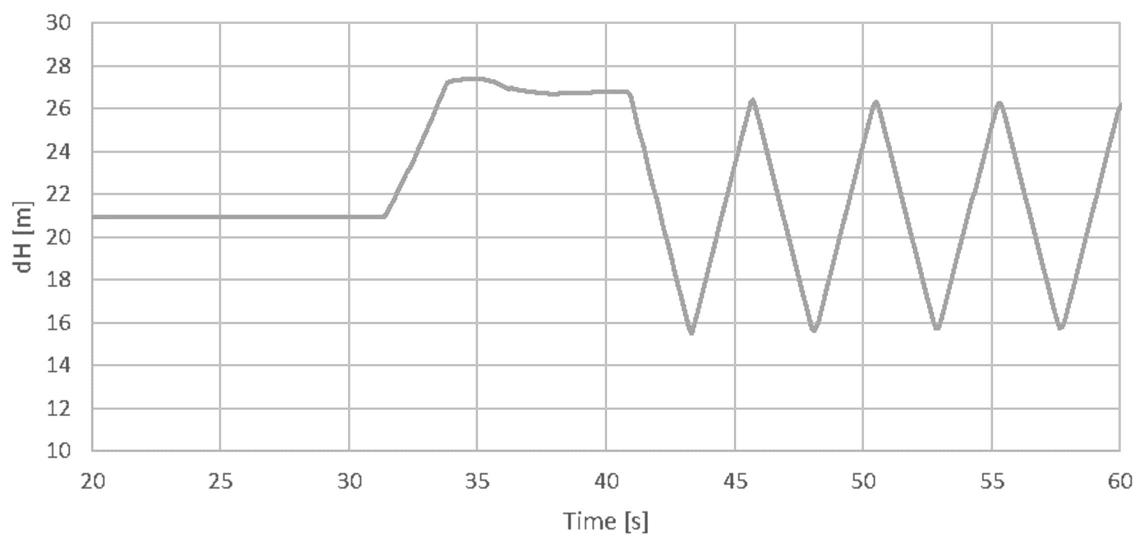


Figure 4.18.: *Pressure increase from shutting down Storvatnet from Q_{max} with a conduit area of 12 m^2*

The pressure increase that is experienced at Storvatnet can easily be designed for as it is less than 7 meters above the head of the power plant.

For Storvatnet an open or closed surge chamber are both possible to use. Deciding which solution is more suitable for Storvatnet should be based on which solution is more practical, effective and economical. In the following section the two surge chamber solutions will be examined.

Firstly the inertia ratio is examined further, by finding the maximum length of which the surge chamber can be placed from the turbine and still fulfill the inertia ratio criteria set by Statnett SF (2012).

$$L_{max} = \frac{13 \cdot 9.81 \cdot 21 \cdot 2.54}{4 \cdot 8} \approx 213 \; [m] \tag{4.28}$$

An open or closed surge chamber can be placed at less then 213 meters from the turbine.

The Thoma criteria for an open surge chamber can then be calculated using the Equation (2.16) with the assumption that the Manning number is equal to 90 for the pipes.

$$A_{Th} = \frac{90^2 \cdot 0.45^{\frac{4}{3}} \cdot 2.54}{g \cdot 2 \cdot 21} \approx 17.3 \; [m^2] \tag{4.29}$$

And the air volume of a closed surge chamber can be calculated using Equation (2.18).

$$V_0 = 1.4 \cdot 21 \cdot 17.3 = 507 \; [m^3] \tag{4.30}$$

Statnett SF (ibid.) says that the PID parameters for a hydropower plant when the net head is less than 100 meters can use the derivative part of the PID parameters, T_d. The common values of T_d is between 0.3 and 1.0. A circular open surge chamber with the Thoma area was first simulated, but gave insufficient results. An increase of the surge chambers diameter to 10 meters gave sufficient phase- and gain-margins after adjusting the PID parameters. The APF-plot in Figure 4.19 has the diameter of the surge chamber is $D = 10\ m$, $P = 5$, $T_i = 12$ and $T_d = 0.3$. Which resulted in a phase- and gain-margin of 33.7° and 3.81 dB, respectively.

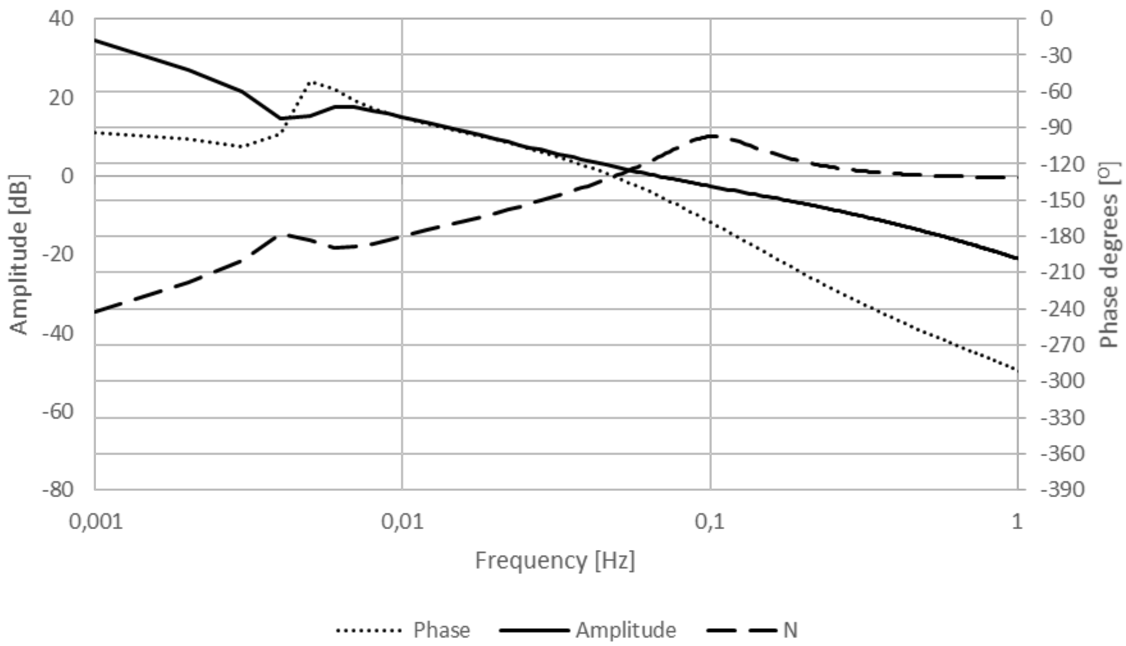


Figure 4.19.: *APF-plot of Storvatnet with an open surge chamber with D=10 m and phase- and gain-margin equal to 33.7° and 3.81, respectively*

Using a closing time of 10 seconds the following water hammer pressure plot seen in Figure 4.20 simulated from 100 % nominal power on an isolated grid. As can be seen the maximum pressure increase will reach 26 meters. With this configuration this will be the design pressure for the pipes used in the conduit as well as the height of the open surge chamber. An increase in the area of the surge chamber will reduce the pressure increase from the mass oscillations.

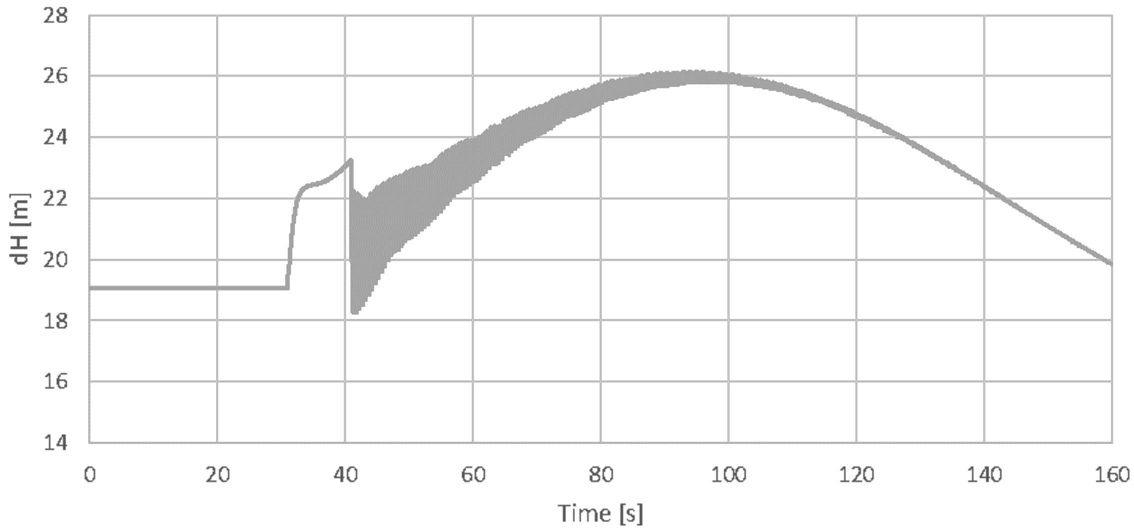


Figure 4.20.: *Water hammer pressure increase for Storvatnet at 100 % nominal power on an isolated grid with closing time of 10 seconds with an open surge chamber with A=17.3 m^2*

A closed surge chamber is a possible solution for Storvatnet. The Svee volume of the closed surge chamber can be calculated using Equation (2.18)

$$V = 1.4 \cdot A_{th}(H_{storvatnet} - H_{surge\ chamber}) = 1.4 \cdot 17.3(111 - 105) = 145\ [m^3] \quad (4.31)$$

With the values of A_{th}, V, the elevation and the initial pressure the surge chamber can be placed in the LVTrans model. We wish to have the surface level during operation at 106 m.a.s.l. and the volume at 145 m^2. To achieve this the initial piezometric head has to be increased to 13.5 mWC.

Since the APF plot will be disregard because of the uncertainties in the Francis turbine parameters the APF plot is not made. The pressure increase in front of the turbine during a shutdown from 100 % nominal power is logged and plotted in Figure 4.21.

The piezometric head increase will be approximately 30 mWC higher than the head, which sets the design piezometric head of the system to 50 mWC. This will also be a design pressure that is possible to design both conduit and turbines to withstand.

During operation, LVTrans simulation shown in Figure 4.22 shows that the maximum and minimum level of the surge chamber will be 116 and 107 m.a.s.l.

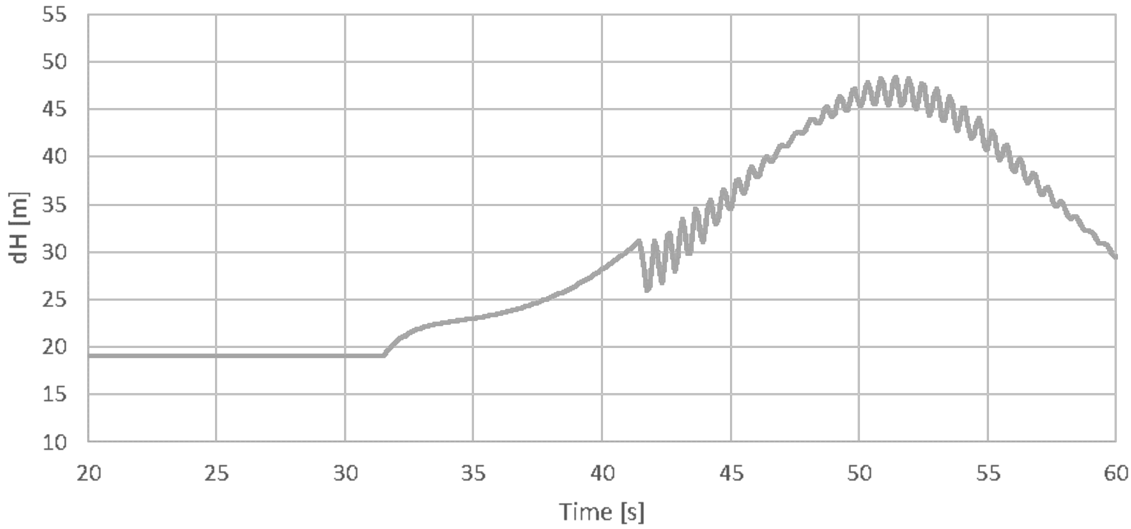


Figure 4.21.: *Water hammer pressure increase for Storvatnet at 100 % nominal power on an isolated grid with closing time of 10 seconds with a closed surge chamber with air volume of 145* m^3

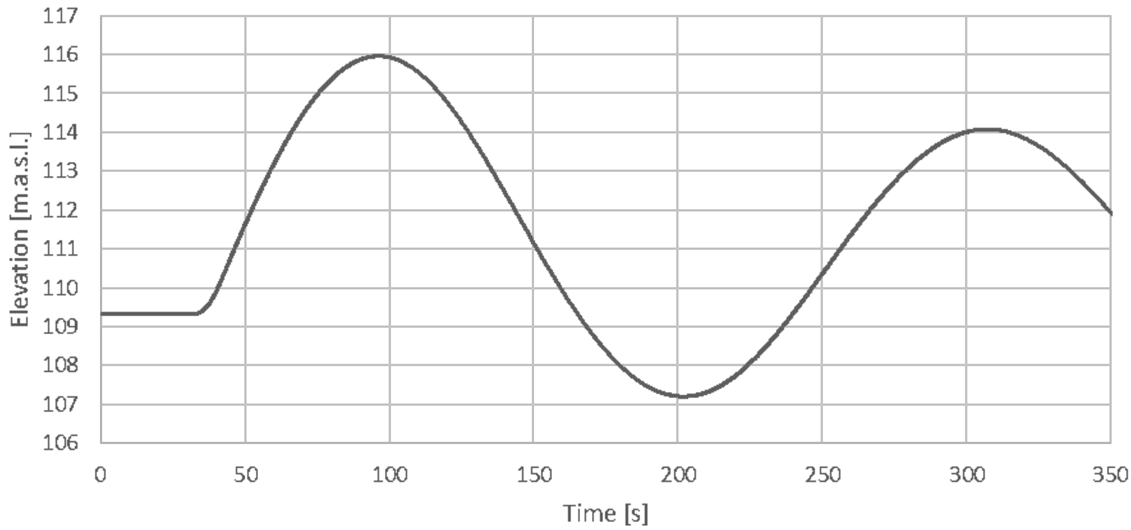


Figure 4.22.: *Minimum and maximum surge elevation of Storvatnet*

4.4. Cost analysis of Storvatnet

Increasing the area of the conduit is a possible solution for Storvatnet. First the conduit that was proposed in the license application has to be examined. Using the collection of prices from SWECO Norge AS (2010b) for small hydropower the cost of a 1.8 meter in diameter pipe which is in total 675 meter long can be found.

The following table shows two possible solutions in increasing the area of the conduit, first the cost of the conduit with a diameter of 1.8 meter is listed. Then the price of a rock tunnel is listed. The minimum area of a rock tunnel is 12 m^2. All the prices are set to the construction price index of 2010, using the resource from SSB (2015) the rise in prices is 16 %.

	A $[m^2]$	Cost $[\frac{NOK}{Consecutive\ meter}]$	Total cost $[10^6$ NOK$]$
Steel pipes	2.54	10 928	7.4
Rock tunnel	12.00	13 920	9.4

Table 4.7.: *Cost of different conduit choices in prices from April 2015, total length of conduits are 675 m for all options*

If a tunnel is chosen the water hammer pressure for the power plant can be calculated when the period of closing, T_L is set to 10 seconds.

$$dh = 2\frac{8 \cdot 675}{10 \cdot 12} = 90\ [mWC] \tag{4.32}$$

This maximum pressure can be tolerated and the use of PE-pipes can be sufficient for piezometric head below 200 mWC. A rock tunnel, compared to the pipes with diameter of 1.8 will cost 2 million more, if a rock tunnel is possible. It is assumed that the rock cover is sufficient to withstand the piezometric head higher than 134 mWC.

If a the rock quality is insufficient, a tunnel will not be possible for Storvatnet. A surge system is therefore examined. The low head of the power plant, and the short distance to the nearby peaks in terrain makes an open surge chamber look like the best alternative when comparing to the high maintenance and technical aspects of a closed surge chamber.

For Storvatnet an open surge chamber with an surface area of 17.3 m^2 was found to be sufficient to ensure regulation stability. The maximum and minimum levels of the surge chamber can be seen in Figure 4.22

An open surge chamber can be laid with pipes with an inclination up the hill on the south side of the conduit. The necessary inclination of a pipe with diameter of 2 m can be found by combining the sinus formula and the area of an ellipse.

$$A_{ellipse} = \pi R_1 \cdot R_2 \tag{4.33}$$

$$R_1 = \frac{A_{ellipse}}{R_2} = \frac{17.3}{1\pi} = 5.5\ [m] \tag{4.34}$$

$$\alpha = sin^{-1}(\frac{2R}{2R_1}) = sin^{-1}(\frac{2 \cdot 1}{2 \cdot 5.5}) = 0.2\ [°] \tag{4.35}$$

The inclination is so low that a 9 meter high surge chamber would be too long if it is laid with pipes. A concrete structure build with the terrain can be sufficient. Examining the terrain and finding the inclination of a potential surge chamber placement is done with the third page in appendix C. The inclination is estimated to be 25°. Assuming the surge shaft is constructed as a square, with length B, that is inclined 25° gives the following necessary area of the concrete construction. Where B_i is the length of the surface area of the water in the inclined surge chamber.

$$A_i = B_1 \cdot B\ [m^2] \tag{4.36}$$

$$sin(\alpha) = \frac{B}{B_i} \tag{4.37}$$

Combining Equation (4.36) and (4.37) gives the minimum length of the surge chamber construction.

$$B = \sqrt{A_i sin(\alpha)} = \sqrt{17.3 sin(25)} = 2.7\ [m] \tag{4.38}$$

The surge chamber has to have a side length of 2.7 meters to have the necessary surface area.

The length, L, of the open surge chamber can be calculated.

$$L = \frac{9}{sin(25)} = 21.3\ [m] \tag{4.39}$$

Assuming a concrete thickness of $t = 1$ meter and that the need for reinforcement is 60 kg per m^2 of concrete gives the following need for materials.

$$V_{concrete} = 2t((B + 2t) + B)B_{opensurgechamber} = 2((2.7 + 2) + 2.7)21.3 = 316\ [m^3] \tag{4.40}$$

This is assuming that also the bottom of the shaft is made of concrete, depending on the rock quality at Storvatnet the need for concrete at the bottom may be unnecessary. The cost is still accounted for as the rock quality is uncertain, which will make the calculation to be more conservative.

And the reinforcement need will be 60 times this, and be approximate 19 000 kg

An 40 % additional cost is added for designing, construction and transport of materials, and an additional 15 % on top of this is set as unforeseen cost. The cost of concrete is found to be 1850 $\frac{NOK}{m^3}$ (SolaBetong, 2015) and the reinforcement cost is 17.15 $\frac{NOK}{kg}$ (Ski Bygg, 2015).

55

	Cost [10^6 NOK]
Concrete	0.58
Reinforcement	0.32
Sum	0.91
Design, construction and transport	0.36
Unforeseen cost	0.19
Total cost	1.46

Table 4.8.: *Cost of an open surge chamber with effective area of 17.3* m^2

The volume of a closed surge chamber that is necessary for Storvatnet is within the size and pressure classification of surge tanks existing on the market. To assess the cost of such a tank the cost is estimated as it was done for the Usma case. The area of the surge chamber is set to 17.3 which results in a diameter of 2.35 meters. The cost of the closed surge chamber can be done with the equations from Irgens (1999).

Calculating the internal piezometric head in the tank with $P_{max} = 50\ mWC$:

$$p = \rho_w g P_{max} = 1000 \cdot 9.81 \cdot 50 \frac{1}{1000^2} = 0.49\ [\frac{N}{mm^2}] \tag{4.41}$$

From the product catalog from Norsk Stål (2015b) a fitting steel plate is found by calculating the σ_ϕ for different thicknesses and checking if this is less than the desing strength of the steel plate. A thickness of 5 mm was sufficient when using the product VV PL S355J2+N.

$$\sigma_\phi = \frac{2347}{5} 0.49 = 230.2\ [\frac{N}{mm^2}] \tag{4.42}$$

$$\sigma_z = \frac{2347}{2 \cdot 5} 0.49 = 115.1\ [\frac{N}{mm^2}] \tag{4.43}$$

The steel volume can be found by calculating the cylindrical steel volume and the volume of the two half spheres. Assuming the height of surge chamber is equal to 9 meters.

$$V_{cylinder} = ((2347 + 5)^2 - 2347^2)\pi 9000 \frac{1}{1000^3} = 0.66\ [m^3] \tag{4.44}$$

$$V_{sphere} = ((2347 + 5)^3 - 2347^3) \frac{4\pi}{3} \frac{1}{1000^3} = 0.35\ [m^3] \tag{4.45}$$

The density of steel is equal to 7800 $\frac{kg}{m^3}$ and the cost of steel is given by Norsk Stål (ibid.) to be 9.7 $\frac{NOK}{kg}$ for the given product. This is used to calculate the material cost for the closed surge chamber.

$$Cost = (0.66 + 0.35)7800 \cdot 9.7 = 0.076\ [10^6\ NOK] \tag{4.46}$$

A compressor and measurement equipment is also needed. This is assumed to be the same as for Usma. Equal to 0.15 million NOK. Table 4.9 shows the cost of a closed surge chamber in steel calculated with the same assumptions of surge chamber cost used in the Usma case, where the cost of designing the chamber is two timest he cost of steel.

The cost is found to be 0.35 million NOK. Storvatnet is expected to produce 6.2 GWh according to the license application. The cost of regulation stability will therefore be equal to $0.06 \frac{NOK}{kWh}$.

The two other solutions, of increased area and open surge tank which were examined for Storvatnet had both an approximate additional cost of 2 millions. The additional cost of achieving regulation stability is 0.3 $\frac{NOK}{kWh}$. The maintenance cost for the solutions for Storvatnet are much lower than what a closed surge chamber would require for Usma.

	Cost [10^6 NOK] V=1000m^3
Steel cost	0.076
Compressor and measurement equipment	0.150
Sum	0.226
Design and construction	0.076
Unforeseen cost	0.045
Total cost	0.347

Table 4.9.: *Cost of a 145 m^3 closed surge chamber in steel for Storvatnet*

4.5. Cost analysis of Tonstad

A rough analysis of the cost involved in the surge chambers for Tonstad hydropower plant. The calculations are based on figures found in the master thesis of Rasten (2014).

Tonstad consists of Four closed surge chambers all excavated in rock, as can be seen in Figure 4.23. The annual production of Tonstad is 3.9 TWh (Sira-Kvina power company, 2013).

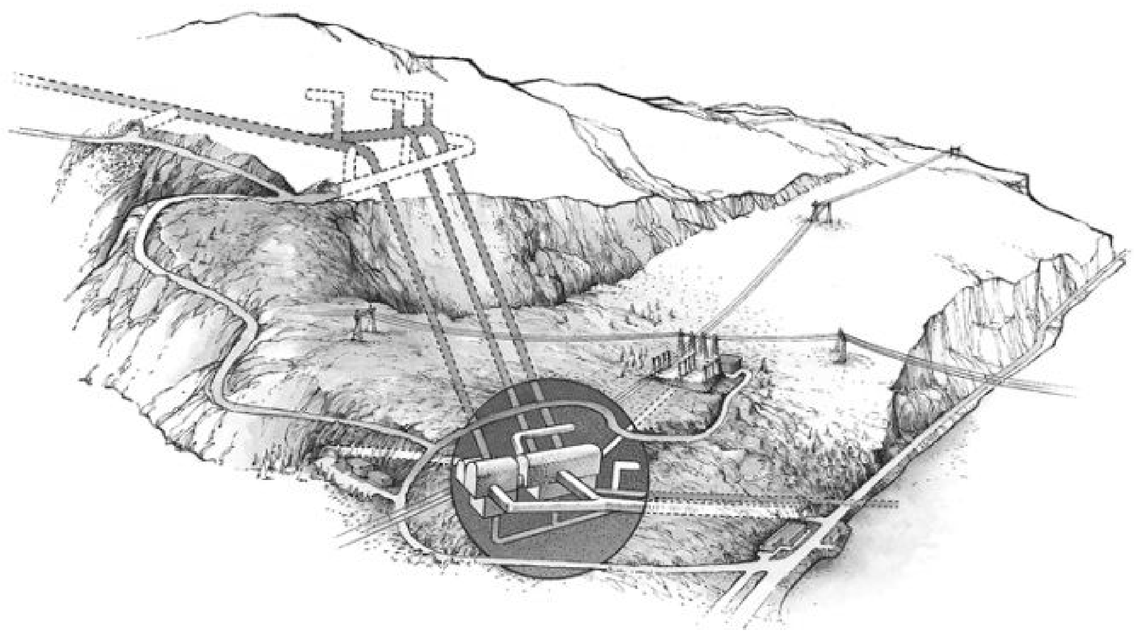


Figure 4.23.: *Tonstad power plant with the three upper surge chamber, and one lower surge chamber (Sira-Kvina power company, 2015)*

There are two levels of both the surge chambers, an upper and lower. The two upper surge chambers are estimated to consist of a 85 meter long 40 m^2 tunnel for the top surge chamber. While the bottom chamber is estimated to be a 40 m^2 and 20 meter long tunnel. The two chambers are connected with a 35 m^2 shaft which is 56 meters long.

Using these values with the cost estimations for large hydropower plants (SWECO Norge AS, 2010a) a cost estimate of the upper surge chamber can be found.

	L [m]	A [m^2]	Cost[$\frac{NOK}{m}$]	Total cost [10^6 NOK]
Top chamber	85	40	0.34	28.9
Bottom chamber	20	40	0.34	6.8
Shaft	56	35	0.08	4.7
Sum				40.4

Table 4.10.: *Cost estimate of upper surge chamber at Tonstad hydropower plant*

The lower surge chamber is assumed to be of the same dimensions of the upper surge chamber. The total cost of the three surge chambers will therefore be three times 40.4 million NOK, which is 161.6 million NOK. Since these calculations are based on several assumptions the uncertainty costs are increased with 100 % of the estimated value. The total cost will then be approximately 320 million NOK.

Tonstad hydropower plant produces 3900 GWh yearly. The cost of the surge chamber compared to the power produced will be: $\frac{250}{3900}$=0.08 $\frac{NOK}{kWh}$.

4.6. Comparison of cases

Combining the results of the cheapest solution from the three cases described above gives the following cost of regulation stability per kWh power produced.

Power plant	Cost $[\frac{NOK}{kWh}]$	Solution
Usma	0.26	1500 m^3 closed surge chamber in steel
Storvatnet	0.06	145 m^3 closed surge chamber in steel
Tonstad	0.08	Four existing closed surge chambers

Table 4.11.: *Cost associated with achieving regulation stability*

5 | Discussion

Achieving regulation stability can be done in several ways, and is very dependent on the terrain and the hydrological condition for the power plant. The different solutions that were expressed in section 3.2, are all possible solutions which can be used in achieving regulation stability. Most of them are tried and tested solutions, while hydrogen production or using a supercomputer is new variations of the heating elements used in older power plants. The responsive bypass valve is an innovative idea that achieves regulation stability only when the flow change is being reduced, unless a percentage of the flow is running through the bypass valve at all times. For small hydropower plants the profit margins are especially low which makes choosing the right solution early in the design process important.

Achieving regulation stability for small hydropower plants proves to be possible for the case studies that has been examined. The method of finding the best solution in achieving regulation stability is similar to what one would do for a larger hydropower plant, but the low profit margins increases the need for innovative solutions and smart choices when working with smaller hydropower plants.

The results were reached by simulating the power plants with LVTrans. Every simulation program will be an estimation of the reality. LVTrans uses the method of characteristics which will give accurate results for simulations that are done in the time domain (Svingen, 2005). Both the Usma and Storvatnet are simple systems with few elements and it is therefore assumed that the quality of the results will for the most part be influenced by the quality of the input data. The accuracy of the simulations are therefore considered to be sufficient for finding estimates for the design choices that are needed to increase regulation stability. The simulation of Usma is considered to be far more accurate than Storvatnet. The reason for this is the high amount of precise data which were gathered from the existing power plant of Usma. The Usma case was also examined previously in a project thesis done by the author, where an emergency stop on Usma and LVTrans simulation of the same scenario was compared. Figure 5.1 shows that the LVTrans model is able to estimate the results, but will not be able to achieve perfectly accurate result.

For Storvatnet the license application was the source for most of the data. Considering the low accuracy of data in license applications and the fact that a non optimal Francis turbine had to be used to simulate a Kaplan turbine in the power plant will give a far less accurate result. Some of the simulations attempt for Storvatnet also resulted in errors, it is hypothesized that the non optimal Francis turbine is the cause of the instabilities experienced at Storvatnet.

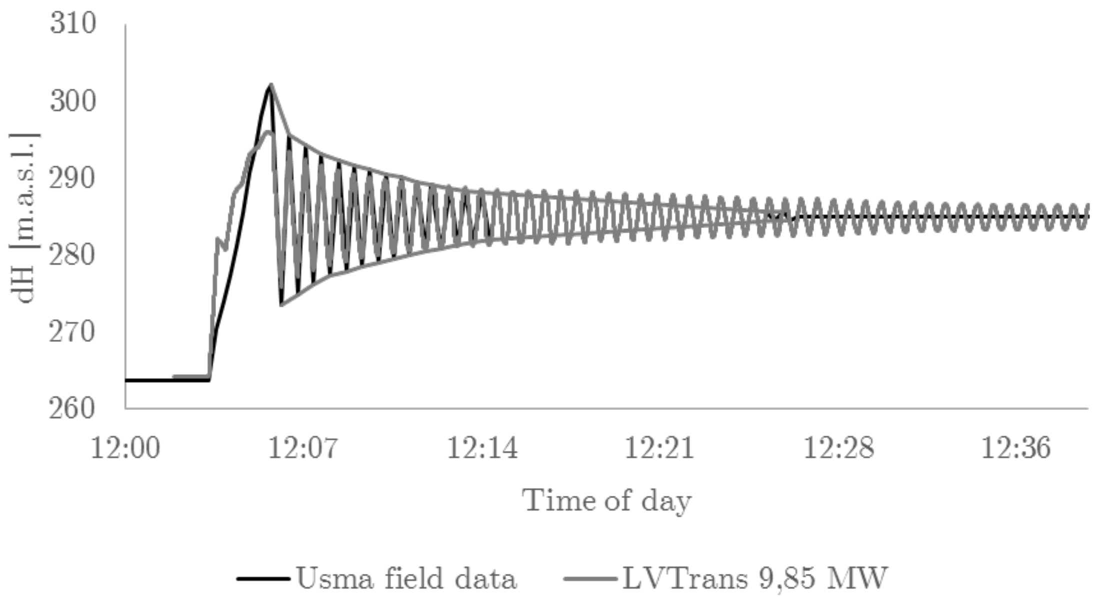


Figure 5.1.: *Comparison between logged data of an emergency stop at Usma and the LVTrans simulation of the same situation*

Usma, is considered to be a difficult power plants to enforce regulation stability on. The power plant, with the longest buried piped conduit in Norway, is just on the border between the definition of a small and regular hydropower plant and has an unusually long conduit compared to other small hydropower plants. The long conduit and relatively high water flow increases the water hammer pressure. Usma was also chosen to examine the possibility to retroactively increase the regulation stability of a power plant that already is built. Which will be the case if regulation stability is required for existing small hydropower plants as well as new hydropower plants.

The assumption that Usma can keep the existing shutdown procedure is a possibility, but it is very dependent on if the solution can be granted by NVE as a safe solution. Since all the mechanical parts are all ready in place at Usma the solution can be an elegant way of optimizing the volume needed for the surge chamber. Since there is a risk that this solution may not be allowed another alternative where the power plant can be shutdown safely over 10 seconds is also examined.

The cost of a responsive bypass valve was also examined in this paper for Usma. Several assumptions of the effects of a responsive bypass valve were made. The assumption that with 10 % of Q_{max} flowing through the bypass valve at any time will be enough to ensure regulation stability is not proven. A precise number for this will vary over the frequency deviations experienced on the grid and the ratio between unregulated power and regulated power production on the grid. Using a time series of the frequency deviation for a grid over a year can give more insight in the designing needs of a responsive bypass valve.

Looking at the graph of the estimated power production and consumption for 2020, seen in Figure 1.1, there are certain times during the summer when the need for regulated power is higher than the rest of the year. A responsive bypass valve will be a cost for the system by the loss of water during operations, but the periods where the responsive bypass valve is active may be chosen. If the periods where the need for a regulation stability on the grid is high then a power plant can operate with the responsive bypass valve. The alternative could be to start a regulated, large hydropower plant to increase the stability of the grid. By introducing large hydropower plants in periods of low consumption, then the small hydropower plants may be forced to shutdown, potentially loosing water that will be overflowing over the spillways since smaller hydropower plants often have no or small basin capacity. The small hydropower plant may therefore have the choice of producing no power, or a reduced amount of power with regulation stability. A responsive bypass valve may therefor be an elegant solution in periods of low load. Further research in the use of a responsive bypass valve would be needed and the amount of water which has to be discharged through the bypass valve to assure regulation stability has to be found.

Because of the uncertainties of the cost of a responsive bypass valve the solution was not used for the cost comparison. This was also the case for hydrogen production and the modern versions of the heating elements.

The Storvatnet case was chosen to examine the cost of a power plant which has an approved license from NVE, but is not yet built. If a new legislation is added that enforces small hydropower plants to be stable then future projects like Storvatnet has to be built with this in mind.

The turbine that was chosen in the simulation for Storvatnet is not the optimal turbine which can be used for the power plant. A Kaplan or bulb turbine would be a better fit because of the low head and high flow of water. Since these two turbines are not implemented in LVTrans a Francis runner which has beta angle values closer to a Kaplan turbine is used. By using a non optimal runner the accuracy of the APF plot will be lowered. In addition, the time constant of inertia for the turbine and generator are especially high, 13 seconds which is ten times as high as a general T_a for small hydropower plants. The reason for the high T_a is because of the low power output and the high rotation speed and high mass of the generator. It is assumed that this number is correct even though it is higher than what was expected.

For Storvatnet, where the head is low, the solution for increasing the conduit area is a possibility and will only increase the design pressure of 7 meters above the head of the system. A rock tunnel will be assumed to withstand these forces and the turbine can also be designed to withstand this pressure. A rock tunnel will only work if the rock quality in the area is of good quality and that the cover above the tunnel is sufficient. If this is not the case then larger pipes may be bought, or constructed for the conduit to reach the necessary conduit area to assure that the inertia ratio criteria is fulfilled.

As previously mentioned, when simulating the APF plot for Storvatnet, with a surge chamber, the simulation gave a not a number (NAN) answer when $T_d = 0$. Increasing this to the minimum general value from Statnett SF (2012) helped the simulation. NAN answer was also came when the power plant was changed from on the grid to isolated grid if T_i was smaller than 10. It is assumed that the PID is not functioning properly because of the non optimized turbine for the power plant. Because of the non optimal turbine and uncertainties in the APF results, the APF plot is disregarded. The plot is still included to show that the possibility of regulation stability is there although this has to be confirmed with simulations with a correct turbine type in another simulation program.

A closed surge chamber can either be made specifically for Storvatnet or bought by a producer of surge tanks. For this case the cost was estimated in the same way as for the Usma case to have a connection between the cost of the two chambers. The cost of maintenance is not estimated in this paper, but a closed surge chamber will be the most expensive of the surge chamber solutions and increasing the conduit area or rotational masses. For the case studies only a singly surge chamber solution was examined. For both the Storvatnet and Usma case several smaller closed surge chambers may be a valid solution and may decrease the cost of the solutions but the alternative was not examined any further in this paper.

The cost estimate done for Tonstad power plant is a very rough estimate with a high degree of uncertainty. The estimated cost is used to shed light on the cost that existing power plants are willing to pay for regulation stability per kWh. The estimation is done very conservative by doubling the cost found with the cost estimation for large hydropower plants, which was done on the basis that the estimations were rough and only the excavation cost were examined.

The cost estimates in this report are based on the work of SWECO Norge AS (2010b) or prices gathered from producers. The cost estimation are assumed to have a high deviation from the actual cost. The estimates are assumed to be similar to what is expected from preliminary cost estimation of ± 20 %. Given the high deviation the cost estimations will only be used to give a picture of the costs involved in achieving regulation stability.

The results from Usma and Storvatnet shows that regulation stability can be reached by the tried and tested methods which has worked for larger hydropower plants. The costs involved in achieving regulation stability appears to be high, but when comparing the cost of regulation stability per kWh produced power the solutions are close to what the estimated cost of regulation stability for Tonstad hydropower plant. If a new legislation is added which requires existing and future small hydropower plants to have regulation stability then the owners will have have to decide: Shutdown the power plant, or achieve regulation stability. It is assumed that the cost of achieving regulation stability added with the future income of the power plant will be a better solution than shutting down the power plant for good.

The key financial ratio for achieving regulation stability can be a good tool for comparing the cost between different power plants, large and small. It has to be noted that for some power plants the cost of achieving regulation stability will be close to zero if for example the portal for the tunneling work is used as an open surge chambers. Considering that many smaller hydropower plants are built with buried pipes, such solutions are often not possible, which requires more expensive solutions such as surge chambers. It is recommended for future work to examine the cost associated with achieving regulation stability in more detail for larger and small hydropower plants. By assessing the cost in the proposed way of cost per kWh, the general cost which the owners and society are already willing to pay for stable power can be examined and compared to the cost of regulation stability for smaller hydropower.

6 Conclusion

The quality of the Nordic grid is said to be unsatisfactory in regards to the quality of frequency. The increasing trend of small unregulated hydropower, interconnecting cables and increased flow of power on the grid are the reasons given by Statnett SF (2014). This will be especially challenging under periods of low load where the small unregulated power plants are dominating the power output on the grid.

As of now the small hydropower plants in Norway are exempt from the requirement of providing stable power to the grid. If a new legislation is passed where small hydropower plants are required to provide stable power, then regulation stability has to be assessed for smaller hydropower plants.

The solutions for achieving regulation stability for small hydropower is found to be the same as for larger hydropower, where the dominating solutions are surge chambers, open or closed, increased conduit area or an increase of the rotating masses. Less common solutions such as heating element can be re imagined by producing hydrogen or super computing, which will help achieve regulation stability while potentially grant another source of income to the hydropower plant. A new proposed solution consists of a responsive bypass valve which can achieve regulation stability at the cost of water loss. The responsive bypass valve can be considered in periods where larger hydropower plants which provides regulation stability for the grid will force smaller hydropower plants to shutdown.

A method of achieving regulation stability was established through the criteria set by Statnett SF (2012). The method is generalized and can be used for smaller and large hydropower production.

A case study were done for two small hydropower plants in Norway, one which is operational, Usma, and one which has acquired its license from NVE, Storvatnet. In both cases the criteria for regulation stability which is set by Statnett SF (ibid.) where fulfilled. The solutions for achieving regulation stability was found to be highly affected by the hydrology, terrain and design choices for the hydropower plant. For existing power plants, such as Usma the solutions found had to account for the existing design choices, while for newer power plants the design choices can be more open for changes without increasing the cost and amount of new construction work.

The cost of achieving regulation stability is proposed to be connected to the key financial ratio of cost per kWh. The two cases were compared to an existing power plant, Tonstad, where the cost of the closed surge chamber solutions were estimated. The following cost comparison were found as can be seen in Figure 6.1.

The cost for achieving regulation stability for small hydropower were found to be lower

Power plant	Cost $[\frac{NOK}{kWh}]$	Solution
Usma	0.26	1500 m^3 closed surge chamber in steel
Storvatnet	0.06	145 m^3 closed surge chamber in steel
Tonstad	0.08	Four existing closed surge chambers

Table 6.1.: *Cost associated with achieving regulation stability*

than expected when compared to existing power plants. And would only increase the total project cost of Usma by 5 %. If the choice is to shutdown the power plant or achieve regulation stability then the solution found would probably be chosen. Although the case studies and comparison object gives a small sample size, the cost of regulation stability is assumed to be of the same cost, or higher than for the existing large hydropower plants. By enforcing regulation stability for small hydropower plants the cost of small hydropower is assumed to increase, which may force some projects to not be built.

For future work it is proposed to further examine existing and future small and large hydropower plants and estimate the cost of regulation stability with the key financial ratio of regulation stability cost per kWh and comparing the difference between large and small hydropower. This may provide further results for the discussion of enforcing regulation stability for small hydropower plants in Norway.

Further research in the less used solutions of achieving regulation stability should also be examined further. Hydrogen production and super computing may be used to regulate power plants and may give a potential of additional income for a hydropower plant. This may in turn reduce the cost of achieving regulation stability. Research for the responsive bypass valve should also be carried out, the solution is hypothesized to be a cost effective solution if it only is required to be used when the grid is unstable.

Bibliography

Brødrene Dahl AS (2015). *BD Vasskraft*. URL: http://dahl.no/Documents/Kataloger/Vannkraft/Vasskraft_small.pdf (visited on 28/05/2015).

European commission (2015). *Establishing a network code on requriements for grid connection of generators, draft*.

Goodall, D. C. et al. (1988). 'Air cushion surge chambers for underground power plants'. In: *Water power & dam construction*.

Guttormsen, O (2006). *Vannkraft og vassdragsteknikk*. Vassdragsteknikk II. Tapir akademiske forlag. Chap. 4, pp. 174–203.

Irgens, F. (1999). *Formelsamling mekanikk*. 3rd ed. tapir akademisk forlag.

Moody, F. L. (1944). 'Friction factors for pipe flow'. In: *Transactions of the ASME* 66, pp. 671–684.

Nielsen, T. (1990). *Dynamisk dimensjonering av vannkraftverk*. Sintef, pp. 49–51, 73–81. ISBN: 82-595-5952-8.

Norsk Stål (2015a). *Varmvalset høyholdfaste plater*. URL: http://produktkatalog.norskstaal.no/Pages/Category.aspx?cat=Org0200&Category=po254040 (visited on 23/05/2015).

– (2015b). *Varmvalset plater*. URL: http://produktkatalog.norskstaal.no/Pages/Category.aspx?cat=Org0200&Category=po255030 (visited on 03/06/2015).

NVE (2012). *Stortvatnet kraftverk, konsesjon*. URL: http://www.nve.no/no/Konsesjoner/Konsesjonssaker/Vannkraft/?soknad=5111&type=11 (visited on 11/05/2015).

Quality Hydraulics (2015). *Hydraulic pulstation surge control equipment*. URL: http://www.qualityhydraulics.com/products/hydraulic-pulsation-surge-control-equipment/ (visited on 19/05/2015).

Rasten, Britt (2014). 'Virkning av hydrauliske transienter på inntaksluker på Tonstad kraftverk'. In:

Rich, G. R. (1969). 'Surge tanks'. In: *Handbook of applied hydraulics*. Ed. by C. V Davis and Sorensen K. E. 3rd ed. McGraw-Hill book company, pp. 1–2.

Sira-Kvina power company (2013). *Welcome to Tonstad power station*.

– (2015). *Tonstad power station*. URL: http://www.sirakvina.no/Prosjekter-og-anlegg/Kraftstasjoner/Tonstad/ (visited on 05/06/2015).

Ski Bygg (2015). *Stål og armerings katalog, Kamstål 12mm*. URL: http://www.skibygg.no/produkter/moertel-betong-stein-staal/staal-og-armering/kamstaal-12-mm-3-00-m (visited on 27/05/2015).

Småkraftforeninga (2014). *Millionbesparelse på smart rørgate*. URL: http://issuu.com/smakraftforeninga/docs/sm__kraftnytt_1/12 (visited on 22/05/2015).

SolaBetong (2015). *Prisliste Betong*. URL: http://www.sola-betong.no/wp-content/uploads/2015/02/Prisliste-2015-Sola-Betong-AS-v2.pdf (visited on 22/05/2015).

SSB (2015). *Byggekostnadsindeks for bustader, april 2015*. URL: https://www.ssb.no/bkibol (visited on 28/05/2015).

Statnett SF (2012). *Funksjonskrav i kraftsystemet 2012*. URL: http://issuu.com/statnett/docs/statnett_fiks_ (visited on 27/02/2015).

– (2014). *Systemdrifts- og markedsutviklingsplan 2014-20*. URL: http://www.statnett.no/Drift-og-marked/Systemansvaret/Systemdrifts--og-markedsutviklingsplan/ (visited on 19/02/2015).

Suzhou Yuda Compressor Co., Ltd (2015). *500 psi air compressor*. URL: http://www.alibaba.com/product-detail/500-psi-air-compressor_60013306741.html (visited on 23/05/2015).

Svee, R. (1972). 'Surge chamber with an enclosed, compressed air-cushion'. In: *International conference on pressure surges*.

Svingen, B. (2005). 'Application of Labview for dynamic simulation of hydraulic piping systems'. In: *SIMS 2005 : 46th Conference on Simulation and Modeling*. Trondheim, Norway: Tapir Akademisk Forlag.

– (2015). *Spørsmål om Ta - svingmassens akselerasjontid*. Personal communication. Principal Engineer at Rainpower and Associate Professor at NTNU.

SWECO Norge (2010). *Veileder i planlegging, bygging og drift av små kraftverk*. URL: http://www.nve.no/Global/Publikasjoner/Publikasjoner%202010/Veileder%202010/veileder1-10.pdf (visited on 11/05/2015).

SWECO Norge AS (2010a). *Konstandsgrunnlag for vannkraftanlegg*.

– (2010b). *Konstandsgrunnlag små vannkraftverk*.

Tveit, K. O. (2015). *Høringsuttalese fra Småkraftforeninga*. URL: https://www.regjeringen.no/contentassets/19b4308c2c69412986c975880a56e4a3/smaakraftforeninga.pdf (visited on 20/05/2015).

Weisbach, J. L. (1848). *Lehrbuch der ingenieur-und maschinen-mechanik: Statik der bauwerke & mechanik der umtriebsmaschinen*. Vieweg.

Wylie, E.B., V.L. Streeter and L. Suo (1993). *Fluid transients in systems*. Prentice Hall. ISBN: 9780133221732.

Yumurtaci, Z. and E. Bilgen (2004). 'Hydrogen production from excess power in small hydroelectric installations'. In: *International journal of hydrogen energy*.

Appendices

A Case Usma

Case Usma

Innledning

Vi vil med dette invitere til å gjennomføre beregninger med ulike programvareløsninger eller teknikker for lastavslag på Usma[1] kraftverk.

Målet med denne sammenlikningen er å gjøre deltakerne litt mer kjent med de ulike programvareproduktene og løsningen som er i bruk. Formålet er ikke å gjøre noen detaljert benchmarking mellom kodene eller forsøke å peke ut noen vinnere.

Alle grupper vil bli bedt om å holde en presentasjon på om lag 20-30 min. Presentasjonen skal inneholde:

1) Introduksjon til programvareløsningen
2) Hvordan sette opp case
3) Resultat [2]

Beskrivelse

Målet med Case Usma er tredelt.
For det første gjør lengden på vannveien at Usma er et litt spesielt anlegg. Dette stiller strenge krav til lukketider. I tillegg vil denne uvanlige vannveien muligens kunne få fram spesielle effekter knyttet til frekvensavhengig viskositet og demping.

For det andre er det planlagt mer detaljerte målinger langs vannveien i forbindelse med en framtidig prosjekt- og/eller masteroppgave ved Vannkraftlaboratoriet ved NTNU. En diskusjon rundt resultatene fra ulike beregninger gir nytt ekstra informasjon i forbindelse med planlegging av oppfølging rundt dette.

Det tredje målet er å vise litt ulike verktøy som er i bruk ved vannveisberegninger og illustrere muligheter og utfordringer knyttet til disse. I så måte kunne man selvsagt heller valgt et tilfelle med en mer komplisert vannvei, gjerne med flere stasjoner, ulike bekkeinntak, svingekammer eller svingesjakter osv. Fordelen med å velge en slik enkel stasjonsutlegging er at man letter i detalj kan vise fram hvordan man gjennomfører beregningene i de ulike verktøy.

[1] Dette gjelder for Usma kraftverk i Selbu, Trøndelag som drives av Trønder Energi. Vi vil takke Trønder Energi for tillatelse til å bruke deres anlegg som tema og for deres hjelpsomhet i forbindelse med innhenting av underlag. Vi vil også takke Rainpower og Hymatek Controls for hjelp med underlag og måledata.

[2] Den enkelte kan velge å gi en oversikt over alle resultat eller fokusere på detaljer i et eller flere tilfeller – se også siste avsnitt av dette dokumentet.

Hoveddata

Anlegg:

Overvann	503 moh
Senterlinje turbin	217 moh
Brutto fallhøyde	286 m

Turbin:

Pelton, 6 stråle
Turtall: n=500 rpm
Merkeeffekt: P = 9.9 MW
(100% slag tilsvarer om lag 11 MW, 80% slag tilsvarer 10 MW)
Lukketid: 240 s på 100% slag.

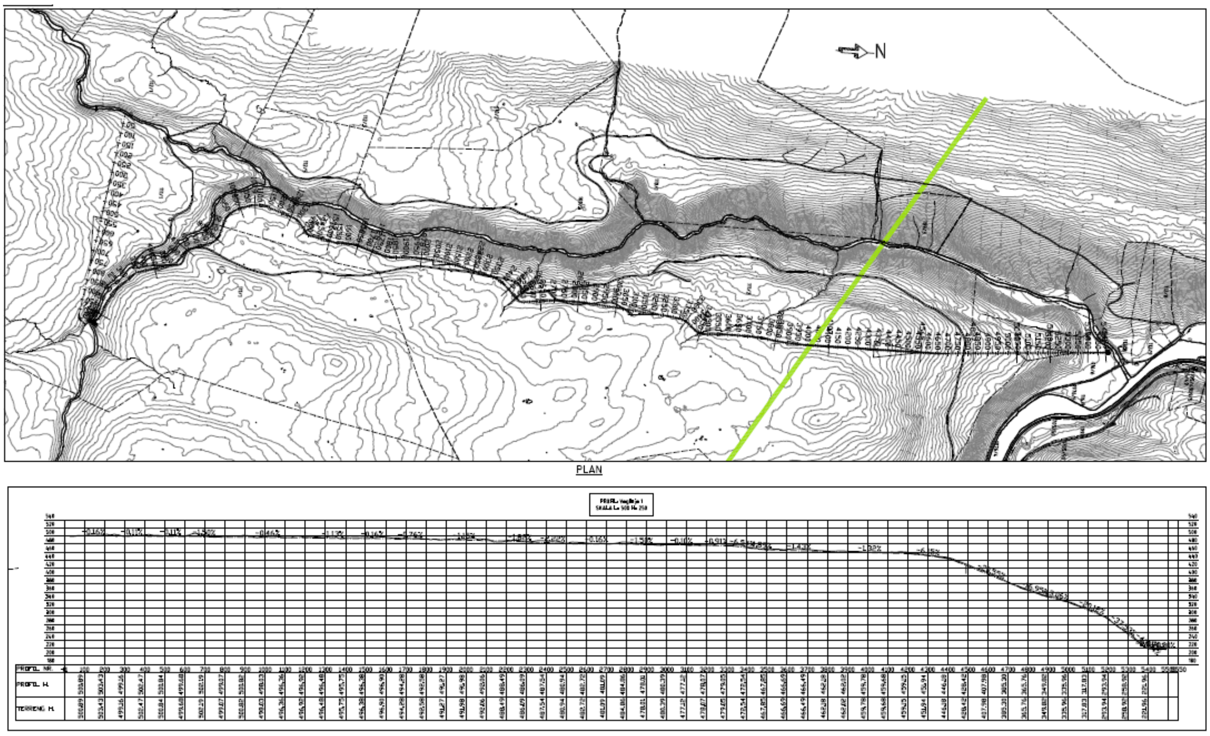
Antatt toppvirkningsgrad: $\eta^* = 90.6$ %

Antatt virkningsgradskurve: $\eta(P) = \eta^* \cdot \left(1 - A \cdot \left(\frac{P}{10} - B\right)^4\right)$

hvor P er effekt i MW, A=3.35 og B=0.68

Treghetsmoment: $GD^2 = 48$ tonn m^2
Antatt generelle data:
Gravitasjonskonstant g=9.81 m/s
Tetthet vann ρ=996 kg/m³

Vannvei:



Figur 1 - Oversikt over rørtrasé for Usma. Ment som indikasjon, ikke for bruk. Tegningen er ganske uleselig. Se tabell under for beskrivelse.

Nr	Beskrivelse	Lengde [m]	Diameter [m]	Start [m.o.h]	Slutt [m.o.h]	Lydhastighet [m/s] [1, 2]
1	GRP – PN6	3372	1.4	499.5	470	420
2	GRP – PN10	972	1.4	470	440	440
3	GRP – PN16	300	1.4	440	380	500
4	GRP – PN20	252	1.4	380	340	530
5	Duktilt stj. – K9	335	1.4	340	268	1018
6	Duktilt stj. – K10	122	1.4	268	238	1044
7	Duktilt stj. – K9	147	1.4	238	217	1067
	Sum lengde =	5500		Midlere lydhastighet=		500.5

Friksjonskoeffisient:

GRP rør [1]	Absolut ruhet k=0.01 mm
Duktile støpejernsrør	Absolut ruhet k=0.03 mm

Merknader:

1) Lydhastighet og ruhet for GRP rør er hentet fra HOBAS katalog
2) Lydhastighet og ruhet for duktile støpejernsrør er hentet fra katalog fra Saint-Gobain

Disse verdiene er gitt som indikasjon. Det er frivillig å benytte andre verdier om en ønsker

Lasttilfeller

I denne omgang legges det kun opp til å gjennomføre beregninger fra lastavslag. Videre vil det kun bli sett på trykkstigning i vannveien. En kan i prinsippet altså droppe å beregne løpehjulet for turbinen. Det eksisterer målinger for lastavslag fra henholdsvis 1 MW, 2.5 MW, 5 MW, 7.5 MW og 10 MW og vi ber dere regne igjennom disse tilfellene.

De personer eller selskap som ønsker å delta med en case vil få tilsendt måledata for disse tilfellene. (se kontaktinformasjon under).

I tillegg ber vi om at alle gjennomfører beregninger for et lastavslag ved P=1.5 MW, vannføring 0.815 m^3/s og pådrag 9%.

Resultat for denne beregningen sendes undertegnede senest 25. august 2014. Data kan sendes enten som ascii-fil eller excel ark med fire kolonner:
Tid [s] Pådrag [%] Vannføring [m^3/s] Trykk turbininnløp [mvs]

For mer informasjon eller for å signalisere at dere ønsker å delta med en beregning ta kontakt med:

Bjarne Børresen,
Energi Norge
bbo@energinorge.no
mob: 92 45 28 38

B | Renting an Atlas Copco compressor

Gmail by Google

Fredrik Staff Edin <fredrik.s.edin@gmail.com>

Leie av kompressor

2 messages

rent@no.atlascopco.com <rent@no.atlascopco.com> Tue, May 26, 2015 at 8:50 AM
To: fredrik.s.edin@gmail.com

Hei Fredrik,

Beklager sen tilbake melding.

Ja når du sier en 260 meter vannsøyle vil det si ca 26 bar.

Da dette er i forbindelse med vann og det ikke ønskes noen form for olje tilført luften må det brukes 100 % olje fri kompressor.

Det billigste alternativet hvis man kan bruke 24 bar er PNS 1250 Diesel drevet kompressor. 100 % olje fri.

Leie vil være ca 9000,- / kalender dag.

Frakt: kommer an på hvor i landet men si at det er i Trondheim kan du beregne 25 000,-

Diesel forbruk kan du se i vedlagt datablad.

Hvis det ønskes et trykk på 26 bar må man inn med en booster + en del annet utstyr.

Da vil dette fort bli dobbelt så kostbart / dag.

Håper dette er tilfredsstillende.

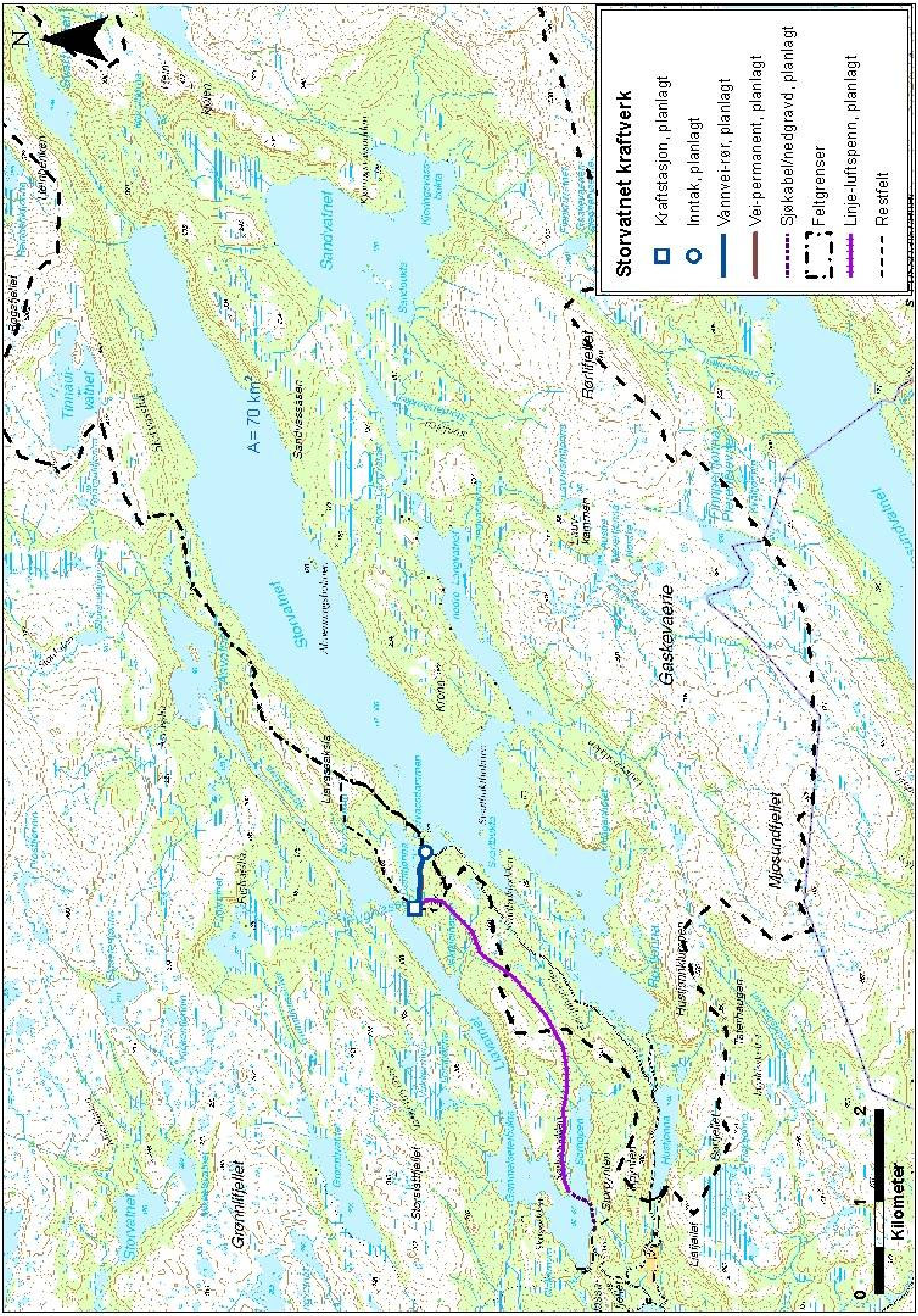
Jeg skriver for øyeblikket masteren min som inneholder kostnadsestimering av ett luftputekammer for et vannkraftverk. Jeg lurer derfor på om det er mulig å få noen generelle kostnader knyttet til kompressorene dere kan levere. Luftputekammeret har ett luftvolum på 1000 m3 og lufttrykket som ønskes å oppnå er på 260 meter vannsøyle og jeg lurer på hvor store kostnader som vil være knyttet mot å kjøpe og eller leie en kompressor som kan passe til en slik luftpute. På forhånd takk - Fredrik Edin

PNS 1250 EN.pdf
162K

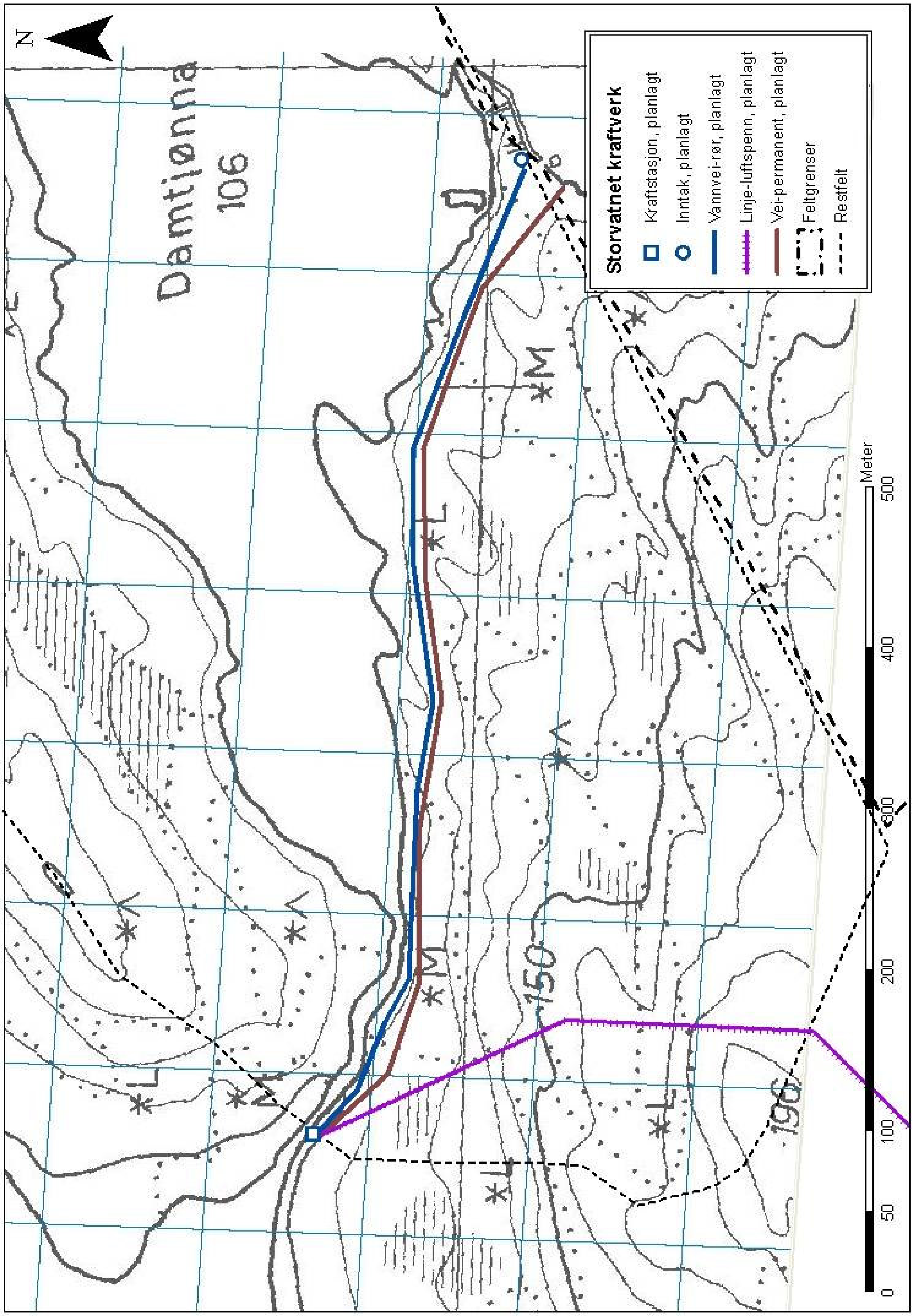
Fredrik Staff Edin <fredrik.s.edin@gmail.com> Tue, May 26, 2015 at 10:04 AM
Draft To: rent@no.atlascopco.com

[Quoted text hidden]
--
mvh
Fredrik Staff Edin
+47 90629631

C | Map of Storvatnet power plant


N
Storvatnet kraftverk
Kraftstasjon, planlagt
Inntak, planlagt
Vannvei-rør, planlagt
Vei-permanent, planlagt
Sjøkabel/nedgravd, planlagt
Feltgrenser
Linje-luftspenn, planlagt
Restfelt
A = 70 km²
Storvatnet
Sandvatnet
Gaskevaerie
Mjøsundfjellet
Rønlifjellet
Grønnlifjellet
0 1 2
Kilometer


Storvatnet kraftverk
Kraftstasjon, planlagt
Inntak, planlagt
Vannvei-rør, planlagt
Vei-permanent, planlagt
Sjøkabel/nedgravd, planlagt
Feltgrenser
Linje-luftspenn, planlagt
Restfelt
Liavassaksla
Storvassdammen
Damtjonna
Fuglvasselva
Svartbuktholmen
Svartbukta
Svartbuktodden
Liavatnet
Rortjonna
Gammelseterbukta
Sorhopen
Storpynten
Litlpynten
Hustjonna
Gronnlivatnet
Storslåttfjellet
Vakkermyra
Lomtjonna
Kilometer
N


N
Damtjønna
106
150
190
Storvatnet kraftverk
Kraftstasjon, planlagt
Inntak, planlagt
Vannvei-rør, planlagt
Linje-luftspenn, planlagt
Vei-permanent, planlagt
Feltgrenser
Restfelt
0
50
100
200
300
400
500
Meter

D | Turbine choice for Storvatnet

Gmail by Google

Fredrik Staff Edin <fredrik.s.edin@gmail.com>

Francis parametre

4 messages

Fredrik Staff Edin <fredrik.s.edin@gmail.com> Mon, May 11, 2015 at 1:49 PM
To: "Svingen, Bjoernar" <Bjoernar.svingen@rainpower.no>

Hei jeg trenger din ekspertise igjen!

Jeg skal nå se på et kraftverk hvor jeg ikke finner turbinparameterne og må derfor finne disse. Jeg har brukt Francis design excel arket som ligger i LVTrans, men får ikke resultater som jeg tror stemmer. Jeg får at antall polpar må være 14 for at beta_2 skal være mindre enn 21 grader. Er ikke dette litt vel mange for et lite kraftverk på 1,4 MW?

Hvordan skal jeg gå fram for å finne gode nok parametre til turbinen?

Nøkkeltallene som jeg har funnet for Storvatnet kraftverk
P = 1,4 MW
H0 = 21 m
Q0 = 8 m3/s
Drør= 1,8m
L = 675 m
--
mvh
Fredrik Staff Edin
+47 90629631

Svingen, Bjoernar <Bjoernar.Svingen@rainpower.no> Mon, May 11, 2015 at 3:03 PM
To: Fredrik Staff Edin <fredrik.s.edin@gmail.com>

Hei

Problemet her er at en liten Kaplan eller rørturbin ville vært bedre enn Francis. Francis vil fungere helt fint, men en optimal en vil gjøre at du får veldig mange polpar pga turtallet. En Kaplan vil kunne rotere hurtigere.

Årsaken er at Q0 er såpass stor i forhold til H0.

Bjørnar

Fra: Fredrik Staff Edin <fredrik.s.edin@gmail.com>
Sendt: 11. mai 2015 13:49
Til: Svingen, Bjoernar
Emne: Francis parametre

[Quoted text hidden]

Fredrik Staff Edin <fredrik.s.edin@gmail.com> Mon, May 11, 2015 at 3:52 PM
To: "Svingen, Bjoernar" <Bjoernar.Svingen@rainpower.no>

Aha,

Er det noe måte å simulere rørturbin eller kaplan i LVTrans?

Hvis ikke så må jeg gå for en francis, bør jeg da ha en uoptimal francis med færre poler? Hvor høy kan beta2 være?

- Fredrik

[Quoted text hidden]

Svingen, Bjoernar <Bjoernar.Svingen@rainpower.no> Tue, May 12, 2015 at 10:12 AM
To: Fredrik Staff Edin <fredrik.s.edin@gmail.com>

Egentlig ikke. For Kaplan har vi et eget program som vi laget for noen år siden. Kaplan er nokså vanskelig, man trenger hele virkningsdiagrammet for alle ledeskovlvinkler og alle løpehjulsvinkler. Man må i prinsippet interpolere i et sett av virkningsdiagrammer. Men til gjengjeld er det typisk null og niks vannvegsdynamikk for en kaplan. Men dette programmet er ikke til allmenn bruk.

Med den fallhøyden og volumstrømmen kan det lønne seg å lage 2 evt 3-4 francis-turbiner. Da vil volumstrømmen per turbin begynne å bli mer normal for en francis, samtidig som turtallet kommer opp, noe som vil redusere kostnad på generator vesentlig.

Du kan kan godt bare øke beta2 til du får et turtall du synes er OK. Det du da gjør er å late som du har en Kaplan. LVTrans vil beregne dette, men hill-chart vil bli feil i forhold til en Kaplan. Men egentlig ikke så galt (vil jeg tro). Du må bare være obs på at du er langt inne i kaplan-land her. Ingen vil finne på å lage en francis med den fallhøyden og volumstrømmen.

BJørnar