Marte Mestvedthagen

Increasing Operational Flexibility of Hydropower by New Technology

Master's thesis in Energy and Environmental Engineering
Supervisor: Pål-Tore Storli
June 2019

Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

NTNU
Kunnskap for en bedre verden

Marte Mestvedthagen

Increasing Operational Flexibility of Hydropower by New Technology

Master's thesis in Energy and Environmental Engineering
Supervisor: Pål-Tore Storli
June 2019

Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

NTNU
Kunnskap for en bedre verden

Preface

This thesis was written at the Water Power laboratory in Trondheim, during the spring of 2019. It is a continuation of my previous, unpublished project work dealing with the same topic. In the process of me finishing my master thesis there are a bunch of people that have earned my appreciation.

First of all thanks to my supervisor, Pål-Tore Selbo Storli for guiding me through my, until now, biggest challenge in life. I would also like to thank Lars Eirik Bakken for explaining me about compressors, Thomas Væringsstad in NVE for providing me information regarding flood and Nea-Nidelvavassdraget, Kaspar Vereide for information regarding thermodynamics in surge chambers and Jørgen Ramdal and Karl Henry Andersen for providing specific data and information about Bratsberg. Thanks to my fellow students at the Water Power Laboratory for a memorable year.

Most of all thanks to my favourite husband Einar for your patience, motivation and trips through my final year. At least thanks to my family for support and to my "extra-family" in Trondhiem, Inga and Eli Kristin for always making me look forward to getting home.

Marte Mestvedthagen
Trondheim, June 2019

Abstract

As the temperature of the planet is rising, climate changes and global warming have become a big part of the politicians agenda. Green and renewable energy is desirable as never before and the energy production from intermittent energy sources as wind and solar increases day by day. Variable production from intermittent sources with no flexibility in time of production generates a need for stabilizing power, balancing the total energy supply. With storage capacity, short response time, high efficiency and reliability hydropower is well suited for this balancing task. In addition to the mechanical challenges consequently varying power production, hydropower plants with outlet to rivers must comply with operational restrictions due to unacceptable environmental impact from fluctuating and rapid alterations in the discharge. Hydropower plants with outlet to rivers are a considerable part of total installed capacity in Norway. Increased operational flexibility for this hydropower plants not at the expense of the river environment is important to increase total hydroelectric flexibility.

This thesis investigate a proposed solution, ACUR LE, Air Cushion Underground Reservoir Low Energy. By introducing an excavated, pressure regulated storage volume for water and air in connection with the tailrace tunnel, ACUR LE intends to control the net flow into the river. A regulated valve and compressor will control the pressure in the chamber and hence the discharge to the river, making it possible to meet today's restriction without decreased flexibility.

This master thesis presents the proceeding of a numerical model for ACUR LE implemented in a case power plant. The numerical model is constructed in MATLAB using the Method of Characteristics and equations describing the dynamics of the turbine, the generator and the regulator. A mathematical expression for the dynamics in the ACUR LE has been developed using the ideal gas law and the assumption of incompressible water. The air flowing through the valve is described in four isentropic ways, depending on the pressure difference in the ACUR LE compared to the outside. The compressor is simplified and is only limited by a maximum mass flow and a maximum rate of change in the mass flow.

The simulations shows that ACUR LE increases the operational flexibility of the case power plant by decoupling the flow through the runers and the discharge to the downstream river. ACUR LE has best effect at startup scenarios where the startup time for the hydropower plant is reduced from 12 minutes to approximately 1 minute! For shutdown scenario the simulations shows that the time it takes to close down the plant can be reduced to 1/6. In addition to this, simulations shows that ACUR LE successfully can imitate natural flow variations, and extract water from the river to reduce small flood peaks.

The model is at an early stage and assumptions leading to simplifications make the model inaccurate and should be looked further into. However, the potential of ACUR LE seems promising.

Sammendrag

Jordas økende temperatur har gjort klimaforandringer og global oppvarming til dagsaktuelle temaer. Grønn og fornybar energi er ettertraktet som aldri før. Energiproduksjon fra uforutsigbare kilder som vind og sol øker dag for dag. Energiforsyning basert på kilder med variabel produksjon genererer større etterspørsel etter forutsigbare, fleksible energikilder for å balansere energisystemet. Egenskaper som kort responstid, lagringskapasitet, høy virkningsgrad og driftssikkert gjør vannkraft velegnet til å utligne etterspørselen i perioder der vind og sol ikke er tilgjengelig.

I tillegg til mekaniske utfordringer knyttet til raske endringer i produksjon, må vannkraftverk med utløp til elv tilpasses restriksjon på hvor rask vannstrømmen kan endres. I Norge er en betydelig del av den totale installerte kapasiteten fra vannkraft, med utløp til elv. Økt operasjonell fleksibilitet for disse kraftverkene uten at det går på bekostning av miljøet, blir viktig for å øke robustheten i det norske og europeiske energisystemet.

Denne masteroppgaven utforsker en foreslått løsning på problemet; ACUR LE(Air Cushion Underground Reservoir Low Energy). Ved å introdusere et trykkregulert lagringsvolum for vann som er koblet på utløpstunnelen er intensjonen at ACUR LE skal kunne kontrollere den totale vannstrømmen som går ut i elva. På denne måten vil vannkraftverket overholde miljømessige krav med hensyn til vannføring i tillegg til å øke sin fleksibilitet.

Denne masteroppgaven presenterer en numerisk modell av ACUR LE, implementert i en modell av Bratsberg vannkraftverk. Modellen er laget i MATLAB ved bruk av karakteristikkmetoden og ligninger som beskriver dynamikken til turbin, generator og frekvensregulator. Et matematisk utrykk som beskriver dynamikken i selve kammeret er beskrevet med den ideelle gassloven og det er antatt at vann er inkompressibelt. Luft som strømmer gjennom ventilen er antatt isentropisk, og tar høyde for fire ulike scenarioer på trykkforskjellen på lufta i og utenfor kammeret. Kompressoren er begrenset med en maksimum gjennomstrømning.

Det er gjort simuleringer for ulike senarioer der ACUR LE er antatt å være fordelaktig. Resultater fra simuleringene viser at ACUR LE er med på å øke fleksibiliteten til eksempelkraftverket ved å gjøre vannstrømmen ut i elva uavhengig av vannstrømmen gjennom turbinene. ACUR LE har størst positiv effekt ved rask oppstart, der tiden kuttes fra 12 minutter til ca 1 minutt og fra 12 til ca 2 minutter ved nedstengning, uten at endringer i volumstrømmen til elven nedstrøms overskrider dagens krav. I tillegg viser simuleringene at ACUR LE kan brukes til å imitere flom, samt trekke ut vann fra elva, for å dempe små flomtopper. Modellen er foreløpig på et tidlig stadium og har mange usikkerhetsmomenter knyttet til seg, som må undersøkes videre, men potensialet til ACUR LE ser lovende ut.

Contents

1 Motivation **1**
1.1 The worlds energy demand . . . 1
1.2 The role of hydropower . . . 1
1.3 ACUR LE . . . 1
1.4 Previous work . . . 2
1.5 Problem description . . . 2
1.6 Limiting the scope . . . 3

2 Background **5**
2.1 Hydropower today . . . 5
2.2 The potential of hydropower . . . 5
2.3 Environmental impact of hydropeaking and varying hydroelectric power production 5
2.4 Scope of opportunity with ACUR LE . . . 6
2.5 Bratsberg hydro power plant . . . 8

3 Theory **11**
3.1 Fluid flow . . . 11
3.2 Thermodynamics . . . 11
3.3 Method of Characteristics . . . 12
3.3.1 Boundary conditions . . . 13
3.3.2 Expanding pipe . . . 14
3.4 Regulator . . . 14
3.5 Turbines and generator . . . 15
3.5.1 Turbine model . . . 16
3.5.2 Connection with Method of Characteristics . . . 17
3.6 Surging devices in HPPs . . . 17
3.6.1 Connection with Method of Characteristics . . . 18
3.7 Compressors . . . 19
3.8 Measuring Volume flow . . . 22

4 Building the model **23**
4.1 Waterway, Turbine and Generator . . . 23
4.2 Elaboration of the ACUR LE . . . 24
4.3 The Regulator . . . 26
4.4 The compressor model . . . 28

5 Results and discussion **31**
5.1 Startup . . . 31
5.2 Shutdown . . . 33
5.3 Flood imitation . . . 35
5.4 Flood mitigation . . . 37
5.5 Superior discussion . . . 38
5.5.1 Model evaluation . . . 38
5.5.2 Evaluation ACUR LE . . . 39

6 Conclusion **43**

7 Further work **45**

Appendices **51**

A Parameters Bratsberg **51**

B A modified rational heat transfer (MRHT) **53**

C Master's Agreement **55**

D MATLAB script for some main elements **57**
D.1 Initialize ACUR LE 57
D.2 Equations ACUR closed valve 58
D.3 Equations ACUR open valve 59
D.4 Equations Turbine 60
D.5 Regulator 61
D.6 Compressor 1 63

E Paper presented at CRHT- IX **65**

List of Figures

1 Pictorial schematic of ACUR LE, not to scale. Redrawn from [8]. 2
2 Power and discharge flow per time with ACUR LE implemented 6
3 Illustration of the flow in different parts of the hydropowerplant for startup and shutdown scenario. Figure 3b redrawn from Moen [9, p.9]. 7
4 Manipulation of the river flow. The illustration is redrawn from Storli [8]. 7
5 Bratsberg power plant in Nea-Nidelvvassdraget. Screen-shot form map provided by NVE [26] 8
6 Characteristic lines in the xt plane. The illustration to the left is showing one calculation and the right figure shows one calculation put into a system 13
7 Surge shaft and surge chamber 18
8 Typical characteristic curve for axial and radial compressor. Redrawn from McMillan [42]. 19
9 Typically operating ranges for different compressors. 1 psig=0.703 mWc and 100 acfm = 0.0472 m^3/s. Redrawn from McMillan [42] 20
10 A customized characteristic map inspired by a characteristic map found in McMillan [42] 20
11 Characteristic curves, the surge curve and the choke curve for a variable speed multistage compressor. Redrawn from *Centrifugal and Axial Compressor Control* [42, p.52] 21
12 An illustration of the sections in the numerical model, not to scale. 23
13 An illustration of the numerical setup for ACUR LE. 25
14 Flow through turbine, Q_{set} and discharge flow during startup, with measurements at the junction between the stand pipe coupled with the tailrace tunnel 31
15 Mass flow through the valve during start up 32
16 Flow through turbine, Q_{set} and discharge flow at shutdown[m^3/s] 33
17 Mass flow through the compressor during shutdown scenario[kg/s] 34
18 Discharge during flood imitation with a preselected Q_{set}. 35
19 Flood imitation with a preselected step by step control variable for the compressor 35
20 Working area for compressor during flood imitation for the two scenarios 36
21 Flow showing water extraction from the river during a flood mitigation scenario. 37
22 Valve operation and the filling of ACUR LE during flood mitigation 38
23 Instabilities occurring during imitation with noise in the measurements and compressor and valve active 40
24 Illustration of regulator parameters during shutdown 40
25 Height of water in ACUR LE during shutdown and startup. 40
26 An illustration of the access tunnel, working as a surge shaft 51

List of Tables

1 Operational restrictions for different scenarios at Bratsberg 9
2 Parameters describing the governing of the turbines 23
3 Water in ACUR LE initially for each case 26
4 Restricted rate of change in the discharge to the river 27
5 Regulator parameters 27
6 Parameters used in MATLAB. (*)linear increase D_{start} to D_{end} 51

List of Symbols

Constants

ρ_w	Density of water	$997kg/m^s$
g	Gravitational acceleration	$9.81m/s^2$
k	Adiabatic constant	1.4
R	Ideal gas constant	$8.314j/(Kmol)$
R_{air}	Specific gas constant for air	$287.058J/(kgK)$

Greek Symbols

δ	Displacement angle	$radins$
η	Efficiency	$-$
κ	Opening degree guide vanes	$-$
ω	Angular frequency	rad/s
ψ	Machine constant turbine	$-$
σ	Dimensionless self governing parameter	$-$
τ	Opening degree valve	$-$
ξ	Pressure loss due to friction	

Roman Symbols

$\bar{H}$	Barometric head	mWc
$\dot{m}$	Mass flow	kg/s
$\tilde{q}$	Dimensionless flow	$-$
$\triangle t$	Time step	s
$\triangle x$	Length increment	m
A	Area	m^2
a	Pressure propagation speed	m/s
A_g	Area of valve opening	m^2
A_s	Surface area	m^2
B	Constant utilized in MOC	s/m^2
b_b	Permanent speed droop	$-$
B_M	Coefficient MOC	$-$
B_P	Coefficient MOC	$-$
b_t	Transient speed droop	$-$

c	Speed of servo motor	m/s
C^+	Characteristic equation MOC	$-$
C^-	Characteristic equation MOC	$-$
C_d	Discharge coefficient	$-$
C_M	Coefficient MOC	$-$
C_P	Coefficient MOC	$-$
C_p	Specific heat	J/kgK
C_v	Coefficient for valve	$-$
D	Diameter	m
e	Error term	$-$
f	Friction factor	$-$
H	Pressure head	mWc
h	Dimensionless head	$-$
H'	Gage pressure	mWc
H_f	Head loss due to friction	mWc
k	Specific heat ratio	$-$
K_p	Proportional gain	$-$
L	Distance between cross sections in pressure-time method	m
L	Pipe length	m
m	Mass	kg
m_s	Dimensionless starting torque	$-$
n	Polytropic exponent	$-$
NP	Number of pole pairs in generator	
P	Power	W
p	Pressure	kPa
q	Leakage loss through turbine	m^3/s
R	Constant utilized in MOC	s^2/M^5
R_m	Mechanical loss constant	$-$
T	Temperature	K
T_a	Acceleration time of rotating masses	s
T_d	Derivative time	s

T_f	Filter constant	s
T_g	Generator torque	Nm
T_i	Integral time	s
T_K	Servo motor time constant	s
T_w	Inflow time of masses of water	s
u_d	Derivative term	$-$
V	Velocity	m/s
V	Volume	m^3
v	Specific volume	$-$
z	Datum level	m

Subscripts

0	User defined starting value
1	Starting point segment
2	End point segment
A	Point before present point in time and space
atm	Atmospheric
B	Point before present point in time and after present point in space
$grid$	Value of grid
h	Hydraulic
i	Present point in space
nom	Nominal value
NS	Last element in pipe
P	Present point in time and space
p	Polytropic
R	Value of reservoir
r	Rated value
ss	Steady state
u	Tangential direction
v	Value of valve

1 Motivation

1.1 The worlds energy demand

In 2018 the energy consumption worldwide grew by 2.3%, nearly twice the average rate of growth since 2010 [1]. With a growing population and a demand for higher living standards the energy need of the expected 9 billion people in 2050 is forecasted to increase by 80% in 2050 compared to today [2]. Global demand for energy is rapidly increasing, due to population and economic growth, especially in large emerging countries, which will account for 90% of the growth in energy demand to 2035 [2]. 195 countries have signed the Paris agreement which aims to limit the temperature increase to 2 degrees Celsius above the pre-industrial levels [3]. To reach this goal the renewable energy production must step up the pace.

Since 2010 the amount of energy from renewables has almost doubled and is today 10% of the global energy mix [4]. Renewables increased by 4% in 2018, accounting for almost one-quarter of the growth in global energy demand [5]. The electricity power sector led the gains, with renewable-based generation increasing at its fastest pace this decade. Solar PV (photovoltaic), hydropower and wind each accounted for about a third of the growth, wind and solar energy production grew by respectively 12% and 31% in 2018 [5].

Norges Vassdrags- og Energidirektorat(NVE) (The Norwegian Water Resources and Energy Directorate) projects increased power production from wind and solar are expected to be doubled within 2030 from todays level. This increase is not exclusively positive. Both wind and solar are intermittent and can not be stored for later use. Hence the power system depends on additional power supply from a stable and reliable source of energy.

1.2 The role of hydropower

Hydropower is the largest renewable energy technology, accounting for around 60% of all electricity supply from renewables and has the ability to store water and hence produce energy when necessary [5].

With more than hundred years of experience hydropower has several advantages over most other sources of electrical power, including high efficiency, a high level of reliability, low operating and maintenance costs, proven technology, flexibility and in many cases; storage capacity. These qualities enable hydropower to act as a battery that can smooth out variation from renewable resources. Traditionally hydropower plants have been used mainly as baseload capacity with some regulation. With increasing intermittent energy sources supplying the power grid, hydropower plants that can provide hydropeaking and quick response will be desirable. *Hydropeaking refers to rapid variations in power production by hydro-electric plants as a consequence of varying electricity generation and fluctuations in demand in the electricity market* [6]. Quick response means that the hydropower plant can provide much power in a relatively short period of time. Flexible hydropower can play a major role in European energy objectives by enabling the increased penetration of intermittent renewables into the power grid [7]. This will lead to more variable hydropower operation which again will lead to varying discharge and rapid alterations. This may influence the river environment in an unacceptable way, unless the water through the turbine can be decoupled from discharge to the river.

1.3 ACUR LE

Air Cushion Underground Reservoir (Low Energy), ACUR LE, intends to mitigate rapid fluctuations of the discharge flow to the downstream river by introducing a storage element for water between the turbine and the outlet to the river. This is illustrated in figure 1. An excavated cavern filled with water and pressurized air is connected to the tailrace tunnel. The idea is to make it work as a regulated surge tank and a “buffer-pool” downstream the turbine. By imple-

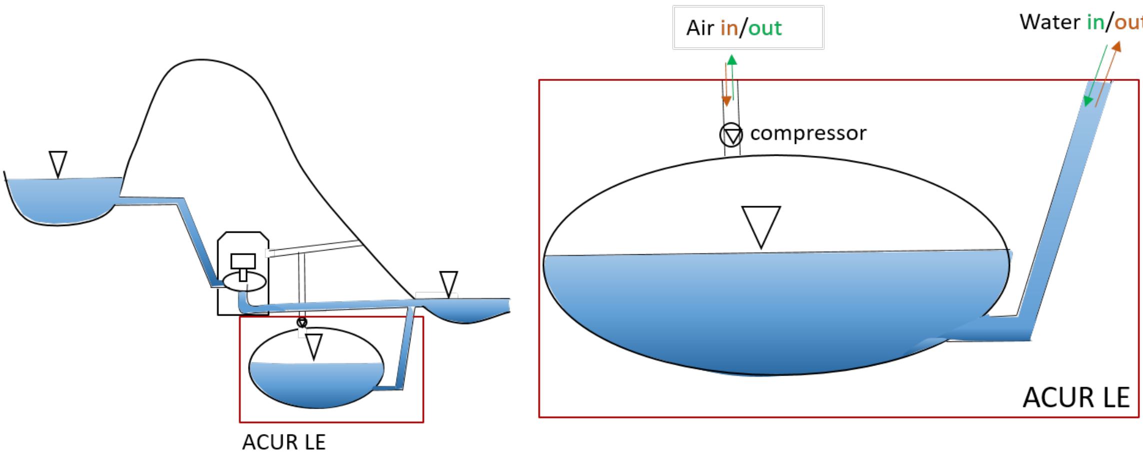


Figure 1: Pictorial schematic of ACUR LE, not to scale. Redrawn from [8].

menting a compressor and a bypass valve controlling the amount of air and hence the pressure in the tank the discharge going in or out of the ACUR LE can dampen the fluctuations and decrease the rapid changes in the discharge to the river. With proper regulation the ACUR LE intends to make already existing power plants operate beyond todays limitations.

1.4 Previous work

Since ACUR LE first was presented by Storli in 2016 [8], the concept has been further investigated by fellow student from the Waterpower Laboratory, Thomas Moen. He wrote his master thesis looking at possibilities and limitations for ACUR LE, together with a proof-of-concept validation[9]. He made a numerical model in the program LVTrans, developing an ACUR LE element with regulation and an implemented simplified compressor. Simulations for different scenarios for start and stop in addition to flood imitation and flood mitigation was performed. Here the conclusion was that the outlook for further studies and investigations was promising. In addition to this the development of ACUR LE is a part of the project HydroFlex. HydroFlex aims to increase the value of hydropower and is founded by the European Union's Horizon 2020 Research and Innovation program[10].

1.5 Problem description

The purpose of this Master's thesis is to further develop the ACUR LE model and gain knowledge about the concept and its pertaining possibilities and limitations. The thesis is investigating ACUR LE by doing the following:

- Literature study on system dynamics and simulations of hydraulic transients in hydropower plants.
- Develop a numerical model for ACUR LE in MATLAB.
- Simulate different operating procedures where ACUR LE is assumed to be beneficial for the case hydropower plant Bratsberg.
- Evaluate the model and the potential of ACUR LE.
- Evaluate requirements for a compressor and valve made especially for ACUR LE.

In addition to this, earlier and further work will be presented as a publication and presented in the conference; 9th International symposium on Current Research in Hydropower Technologies

(CRHT-IX) at Kathmandu University. The original tasks in the master agreement can be seen in appendix C.

1.6 Limiting the scope

ACUR LE is a complex idea and this thesis is limited to aspects considering the technological feasibility of the concept. The model will be limited to one case-hydropower plant and simplifications regarding some of the components ACUR LE consist of, such as compressor dynamics and thermodynamics. These simplifications will be further evaluated and discussed. The economical aspect will not be considered beyond motivation and some thoughts regarding profitability.

2 Background

2.1 Hydropower today

Renewable energy represented 29.6% of the European energy mix in 2016, of which 10.7% came from hydropower. In Norway hydropower is by far the biggest power supplier with about 94% of the power production [11]. In 2018 the average annual production was calculated to be 134.9 TWh, this is about 62% of the impressive 212 TWh estimated hydropower potential in Norway [12]. Out of Norway's 32.3 GW installed hydropower capacity, approximately 15% (5.6GW) is storage plants with upper storage reservoir and outlet to river [13].

2.2 The potential of hydropower

As hydropeaking probably will be more normal, not only for daily demand peaks, but to cover energy demand when intermittent renewables can't be utilized, hydropower may play a major role in the future energy system. Statnett are responsible of balancing the energy market in Norway. After the response time, the balance market can be divided into primary (FCR), secondary (FRR-A) and tertiary reserves (FRR-M). Of these, FCR is the fastest, while FRR-M is the slowest with 15- minutes response time. The reserves are activated as needed and with time-resolved marginal pricing, where the hydropower plants with the fastest response time has the highest prices.

From a power production perspective, the water stored should be exploited in a way that maximizes the economic return. Due to the varying energy production from intermittent renewables, Norges Vassdrags- og Energidirektorat(NVE) (The Norwegian Water Resources and Energy Directorate) predicts increased subdaily price variation in the years to come. This gives storage hydro power plant with short response time an economic advantage [14]. It will be crucial for future energy systems that the absence of intermittent energy production can be covered. To cover the future energy demand by hydropeaking with today's hydropower plants, the discharge limitations will be exceeded and be at the expense of the ecosystem in rivers downstream the hydropower.

2.3 Environmental impact of hydropeaking and varying hydroelectric power production

It is an extensive widespread concern among scientists that river exploitation results in loss of biological diversity and ecological degradation. The integrity of a river depends largely on its natural dynamic character [15]. The flow varies on multiple temporal scales, from subdaily variations in minutes and hours, to days, months or even decades (climate changes) [16].

Hydroelectric power production will intrude the natural flow variations and hence affect the ecosystem in the river. Dewatering in connection to hydropeaking results in the alteration of hydrological characteristics of downstream flow. These artificial fluctuations create unnatural phenomena of various magnitude, duration, timing, thermal waves, rate of change and frequency of changes in flow that will impact river ecosystems [17] [6]. Fishes, macroinvertebrates and aquatic plants undergo a major stress due to hydropeaking and often they are not able to survive these frequent water level fluctuations [17]. Life cycles of many aquatic and riparian species are timed to either avoid or exploit the natural flow variations in a river [18]. Therefore the timing, or predictability, of flow events is critical for the ecosystem.

The major challenges for the fauna in rivers adjacent to the discharge of hydropower plants under a hydropeaking are dewatering and stranding [19]. Fish stranding is any event in which fish are restricted to poor habitat as a consequence of physical separation from a main body of water[20]. Susceptibility to stranding is a function of behavioral response to changing flows, and this varies with species, body size, water temperature, time of year and day, morphology, and the rate of flow reductions [18]. Rapid dewatering has a direct mortality effect on fish, due to stranding, and an indirect effect due to desiccation or drift of the benthos [21]. For the salmon hydropeaking can lead to mortality in early life stages, with higher impact on the alevins as they have lower tolerance to dewatering than the eggs [22].

There are three principal methods to reduce hydropower impacts: morphological, constructive measures and operational [20]. The morphological measures aims to improve river characteristics with areas suitable for the biotic system. Constructive measures decrease the hydropeaking flows downstream the outlet. This is done by building basins, bypass tunnels and dikes. The operational measures focus on adjustments of the power production. It involves a minimum and maximum discharge and limitations when it comes to dewatering. Yin et Al. studied how modifications in operational procedures could help mitigating some of the inconvenient hydropeaking introduce to the river environment [23]. This study shows that changes in operation can improve stream conditions and reduce stranding risk for brown trout. It should be possible to reduce stranding by ecologically adjusted operational procedures and by considering both diurnal and seasonal considerations when dewatering rivers [21]. However, implementing operational restrictions like maximum dewatering rates and high minimum flows can incur high cost for the power company compared to their ecological effectiveness [24].

In order to effectively implement mitigation measures in regulated rivers, environmental flow release mimicking the natural hydrological and thermal regime are the optimal solution to mitigate impacts to ecosystems [22].

2.4 Scope of opportunity with ACUR LE

ACUR LE is in the intersection point of constructive and operational measures as it is a hydraulic structure that will influence the limitations regarding power plant operation. With intended use of ACUR LE, limitations considering the change of discharge flow can be averted, as the discharge to the river will be decoupled from the flow through the turbines, as illustrated in figure 2.

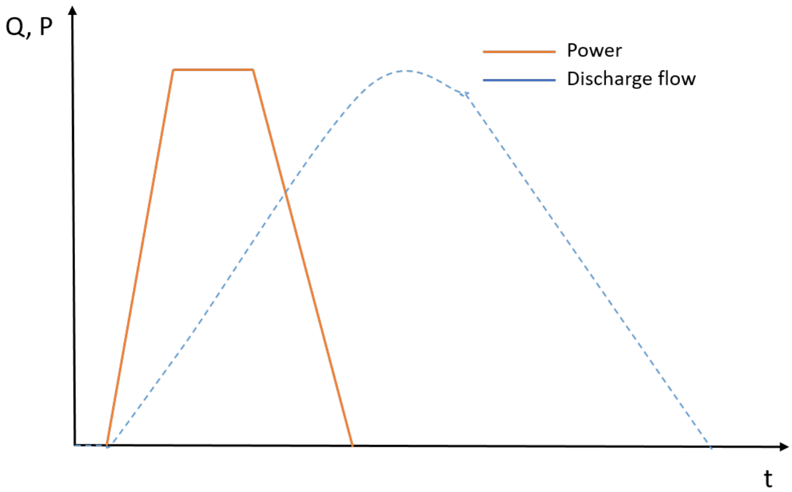
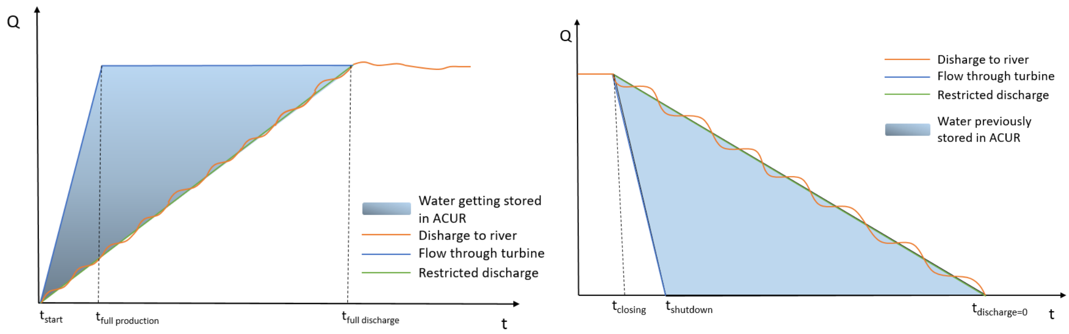


Figure 2: Power and discharge flow per time with ACUR LE implemented

This decoupling is made possible through the excavated chamber, the compressor and the valve, as figure 1 shows. During an increase in power production the valve will open, then the air inside the ACUR will exit through the valve as the pressure inside ACUR is higher than the atmospheric pressure at the outside. This decrease in pressure will make water from the tailrace tunnel flow into ACUR LE instead of out to the river, hence decreasing the rate of change in the discharge flow to the river.

The possibility of fast regulation beyond todays limitation will also potentially increase the economic outcome. This makes it possible to shutdown faster at low electricity prices, saving that water for times with higher prices. In addition to fast increase of power production when the prices are high. An example of a hypothetical case showing the discharge flow to the river, the restricted discharge and the water flowing to ACUR LE during startup can be seen in figure 3a.

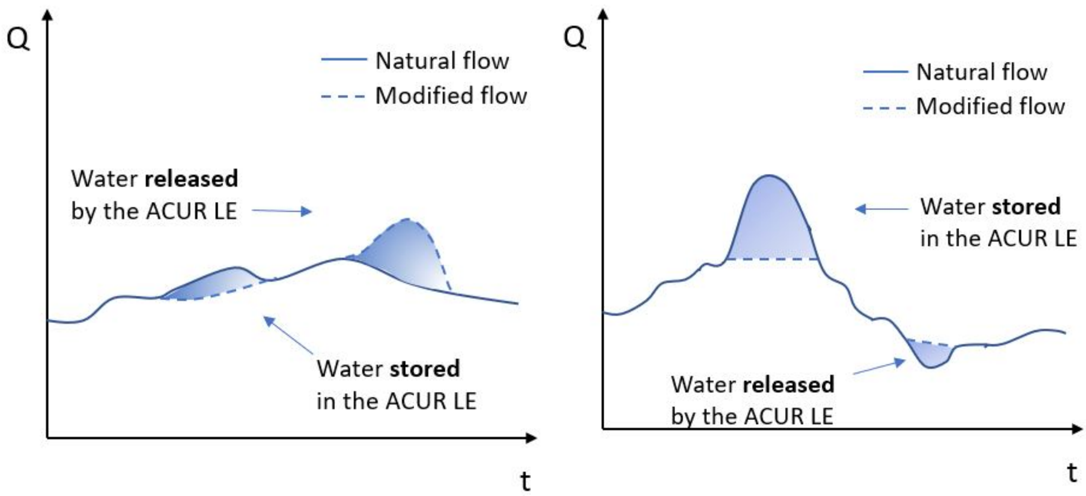


(a) Startup scenario

(b) Shutdown scenario

Figure 3: Illustration of the flow in different parts of the hydropowerplant for startup and shutdown scenario. Figure 3b redrawn from Moen [9, p.9].

For a decrease in power production the scenario will be a bit different. If the decrease is higher than the restricted rate of change the compressor will be utilized. As the compressor start to work the amount of air added by the compressor will increase the pressure in the ACUR LE. As a result, water stored in the ACUR LE will be pushed into the tailrace tunnel, adding stored water to the discharge from the turbine. By controlling the pressure in ACUR LE the total discharge can be controlled and continuous measurements and regulation will keep the rate of change in the discharge at an acceptable level during shutdown. This is illustrated in figure 3b



(a) Flood imitation

(b) Flood mitigation

Figure 4: Manipulation of the river flow. The illustration is redrawn from Storli [8].

By implementing ACUR LE hydropower plants can be a positive contribution to the river ecosystem beyond the hydropeaking scenarios. As described previously in section 2.3 the river ecosystem is depending on natural flow variations. These natural variations can be imitated and hence the problem with lack of spring flood can be solved, as shown in figure 4a. Floods are not merely positive, and during extreme flood, ACUR LE can be used to store water from the most destructive parts of the flood, the flood peaks. This has been illustrated in figure 4b.

Together with dams or/and pump storage, implemented ACUR LE working as intended would evolve the flexibility regarding power plant operation and hence gain the economical potential. In addition to this it can be used to imitate natural variations in the river flow and flood mitigation. That will be a positive contribution to the river ecosystem beyond the hydropeaking scenarios and improve the river ecosystem.

2.5 Bratsberg hydro power plant

In order to investigate the performance and evaluate the feasibility of ACUR LE, Bratsberg hydropower plant is used as a case for simulations. Bratsberg hydropower plant started producing energy in 1977 and is located in Trondheim, Norway. Two installed Francis turbines utilizes the 147 m net head from Selbusjøen to produce a total of 124 MW at its maximum [25]. The

Figure 5: Bratsberg power plant in Nea-Nidelvvassdraget. Screen-shot form map provided by NVE [26]

.

average annual production is 650 GWh.

From Selbusjøen there is a 16 km long transmission tunnel via Bratsberg power station before discharging into Nidelva. A surge shaft is implemented just before the penstock. After each draft tube there is a shaft for the sliding gate. These two shafts act as stand pipes. In addition to this the access tunnel acting as a surge chamber. The access tunnel is mutual for the two stand pipes and has a cross sectional area of 25 m^2 and a 15% gradient. The reservoir, hydraulic conduits and position of the powerhouse cavern, as well the three other hydro power plants Leirfossen, Øvre Leirfossen and Nedre Leirfossen can be seen in figure 5.

The lower 8 km of Nidelva, from the sea upstream to the outlet of Bratsberg, is a well-known salmon river [27]. In the salmon season Bratsberg hydropower plant is allowed to reduce the power by 43MW/h. This means that from a maximum production at 124MW it will take approximately 2.88 hours to shut down. The operating restrictions are provided by Statkraft and can be seen in table 1.

	Duration startup [s]	duration shutdown [s]	Load difference[MW]
Outside salmon season	360	360	62
Salmon season	3600	3600	65(start) and 43(stop)

Table 1: Operational restrictions for different scenarios at Bratsberg

3 Theory

This chapter will give an overview of the theory used to develop the simulation model made for this thesis. First, general theory about fluid flow and thermodynamics are explained before a section describing Method of Characteristics follows. Further, equations describing the behaviour of different key elements in a HPP is included. Lastly some relevant theory about compressors are presented.

3.1 Fluid flow

Fluid flow is either constant, steady-state, or changing with time, transient. For a steady state flow in a hydro power plant the properties can be found by the energy equation[28]:

$$H_1 + \frac{V_1^2}{2g} = H_2 + \frac{V_2^2}{2g} + H_t + H_f \tag{3.1}$$

H, V and g is the pressure head, mean velocity and the gravitational constant respectively. The subscripts 1 and 2 is before and after the turbine. H_t is the head used in the turbine and H_f is the head loss in the system due to friction. The head loss in a pipe can be calculated by the Darcy-Weisbach equation[28]:

$$H_f = f\frac{L}{2gD}V^2 \tag{3.2}$$

where L is the length of the pipe, D is the diameter of the pipe and f is the friction factor. The friction factor is dependent of the relative roughness of the wall and Reynolds number, Re. In this thesis some simplifications have been made and a constant f for each pipe is used, independent of Re.

Continuously change in power demand leads to flow variations and hence transient fluid properties. The transient flow is governed by two partial differential equations(PDE)'s, the equation of motion and the continuity equation. The equation of motion states that the sum of forces is equal to the fluids mass times its acceleration. It can be simplified to a hydraulic-grade-line form, seen in equation 3.3. This simplification is restricted to less compressible fluids, such as liquids, flowing at low velocities [29].

$$g\frac{dH}{dx} + \frac{dV}{dt} + \frac{fV|V|}{2D} = 0 \tag{3.3}$$

The continuity equation expresses the connection between the accumulated mass of water and the entering and exiting flow. A simplified hydraulic line form applicable for low velocities and less compressible fluids is given below[28]:

$$\frac{a^2}{g}\frac{dV}{dx} + \frac{dH}{dt} = 0 \tag{3.4}$$

The pressure propagation velocity, a, is approximately 1200 m/s for fluid flow[28]. To solve these equations expressing transient flow the Method of Characteristics is utilized as explained later.

3.2 Thermodynamics

At states where the pressure p is small relative to the critical pressure p_c and/or the temperature T is large relative to the critical temperature T_c it can be assumed with reasonable accuracy that the ideal gas equation of state applies[30, p.100]:

$$pV = mRT \tag{3.5}$$

where V is volume, m is the mass and R is the ideal gas constant. There are many different thermal processes that can occur, some relevant for this thesis are explained here.

Isothermal process: A process that occurs at constant temperature.

Adiabatic process: A process with no thermal interaction with the surroundings. Meaning the heat transfer for the process is zero.

Isentropic: An isentropic process is a reversible adiabatic process. Meaning no dissipative effects and the system neither absorbs nor gives off heat.

Polytropic process: A polytropic process of a closed system can be described by a pressure-volume relationship of the form[30]:

$$pV^n = C \tag{3.6}$$

where C is a constant, and the exponent n can take different values depending on the thermal process. If the process is isothermal n=1. and for an isentropic process $n = k$ where k=specific heat ratio=C_p/C_v.

3.3 Method of Characteristics

The Method of Characteristics (MOC) enables the numerical solution of the equation of motion and the continuity equation based on a set of assumptions. The assumptions include neglecting the convective acceleration terms, which is acceptable for slightly compressible, low Mach number flows, such as transient flow in water power systems[29]. The following subsection is explained more in detail in the book *Fluid Transients in Systems* by Wylie and Streeter and the equations can be found there [29]. The MOC transforms the PDF's, equation 3.3 and 3.4, into two pair of Ordinary Differential Equations (ODE)'s, the compatibility equations C^+ and C^-.

$$C^+ : \begin{cases} \frac{g}{a}\frac{dH}{dt} + \frac{dV}{dt} + \frac{fV|V|}{2D} = 0 & \text{(3.7a)} \\ \frac{dx}{dt} = a & \text{(3.7b)} \end{cases}$$

$$C^- : \begin{cases} -\frac{g}{a}\frac{dH}{dt} + \frac{dV}{dt} + \frac{fV|V|}{2D} = 0 & \text{(3.8a)} \\ \frac{dx}{dt} = -a & \text{(3.8b)} \end{cases}$$

The compatibility equations are only valid on the appropriate characteristic line. Equation 3.7a and 3.8a are valid along the characteristic lines plotted by the equation 3.7b and 3.8b. This can be visualized as shown in figure 6. The point A and B refer to the points in space before, $(x = i-1)$, and after, $(x = i+1)$, point P, $(x = i)$, and P occurs $\triangle$t after A and B. That means that in point P, the equations have the same two unknowns, dH/dt and dV/dx, which can be solved, valid for position P, in the xt plane. Q/A is used for V.

The ODE's can be integrated to yield finite difference equations, which can be solved numerically:

$$C^+ : H_P = C_P - B_P Q_P \tag{3.9}$$

$$C^- : H_P = C_M + B_M Q_P \tag{3.10}$$

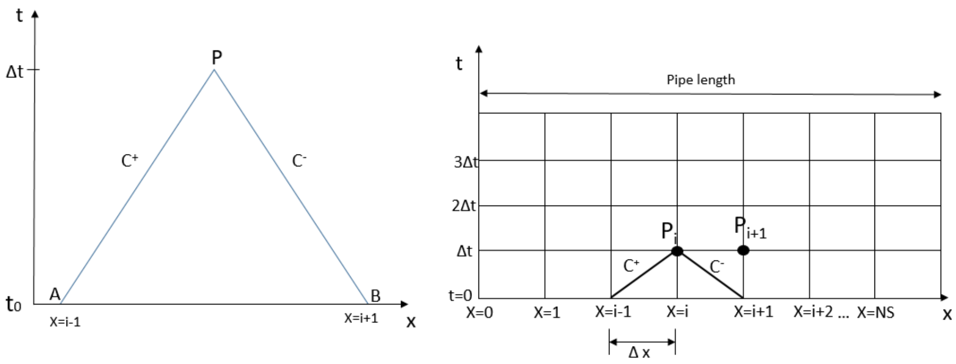


Figure 6: Characteristic lines in the xt plane. The illustration to the left is showing one calculation and the right figure shows one calculation put into a system

where

$$C_P = H_A + BQ_A \qquad B_P = B + R|Q_A| \tag{3.11}$$

$$C_M = H_B - BQ_B \qquad B_M = B + R|Q_B| \tag{3.12}$$

and

$$B = \frac{a}{gA} \tag{3.13}$$

$$R = \frac{f\triangle x}{2gDA^2} \tag{3.14}$$

A pipeline is divided into N number of reaches, each with the length $\triangle x = \frac{L}{N}$, where $N = 3$ is the smallest value of dividing parts. The time-step for the system is defined by the shortest pipe-element as: $\triangle t = \frac{\triangle x}{a}$. To solve the equations at the point valid for both characteristic equations it is important that $\triangle t$ is equal in all equations. As shown in figure 6.

In a pipe system each element is solved for itself at each time step, and the end-sections of each element is found by additional equations describing the end condition of the element. With proper boundary and initial conditions the variables Q and H can be found through an entire pipe system, simulated over a defined time.

3.3.1 Boundary conditions

At each end of a single pipe only one of the compatibility equations is available in the two variables. That means an additional equation is needed in each case that specifies either Q_P, H_P or some relation between them. Following boundary conditions have been defined:

Upper or lower reservoir: If the start or end of a pipeline is an upper or lower reservoir the head is at that point defined as[29]:

$$H_P = H_R \tag{3.15}$$

Junction: Two pipes connected in a series or more pipes in a junction have end functions defined by the continuity equation. Hence, the sum of the flow in and out of a junction should set to zero. Also the pressure head is set equal for all pipes:

$$H_i = \frac{\Sigma C_P/B_P \Sigma C_M/B_M}{\Sigma(1/B_P + 1/B_M)} \tag{3.16}$$

Where C_P and B_P refers to the pipes entering the series/junction and C_M and B_M refers to the pipes exiting. The flow in the first, 1, or the last element, NS, of the pipe is calculated as:

$$Q_{1,NS} = \frac{C_{P1} - H_P}{B_{P1}} \tag{3.17}$$

$$Q_{2,1} = \frac{H_P - C_{M2}}{B_{M2}} \tag{3.18}$$

Here pipe 1 enters the junction, while pipe 2 exits. This calculations are applicable independent of the number of pipes entering and exiting the junction.

Valve: For a valve some assumptions are made, no inertia effects in accelerating or decelerating flow through the valve opening, no change of volume or volume stored in the valve. Hence, continuity equation is applicable and states that $Q_{1,NS} = Q_{2,1}$. Across the valve there is a drop in the hydraulic grade line, H_0, at steady state, $Q = Q_0$ and at fully open valve, $\tau = 0$. The orifice equation for positive flow is[29]:

$$Q_v = \frac{Q_0 \tau}{\sqrt{H_0}} \sqrt{H_A - H_B} \tag{3.19}$$

Where H_A and H_B respectively is the head at the end of pipe 1 and beginning of pipe 2. Rewriting the above equation gives an expression of the head loss, H_0, over a valve during steady state flow, Q_0:

$$H_0 = \frac{Q_0^2}{2g(C_d A_g)_0^2} \tag{3.20}$$

Where $C_d A_g$ is the area of the valve opening times the discharge coefficient. When combining the orifice equation with equation 3.9 and 3.10 a quadratic equation can express the flow going through the valve[29]:

$$Q_v = -SC_v(B_{P1} + B_{M2}) + S\sqrt{C_v^2(B_{P1} + B_{M2})^2 + 2SC_v(C_{P1} - C_{M2})} \tag{3.21}$$

where $C_v = Q_0^2 \tau^2 / 2H_0$ and S is set to +1 if $C_{P1} - C_{M2} \geq 0$ and -1 if $C_{P1} - C_{M2} < 0$ [29].

3.3.2 Expanding pipe

The equations below are derived from the equations of motion and continuity for an expanding section. They are developed by NTNU-student Anna Holm Hafret and differ from the ones stated in *Fluid transients in systems*, as they appeared to be wrong[31, p.7]. The equations neglect friction and are as follows:

$$Q_P = \frac{\frac{g}{a}(H_A - H_B) + \frac{1}{2}Q_B(\frac{1}{A_P} + \frac{1}{A_B}) + \frac{1}{2}Q_A(\frac{1}{A_P} + \frac{1}{A_A})}{\frac{1}{A_P} + \frac{1}{2A_B} + \frac{1}{2A_A}} \tag{3.22}$$

$$H_P = H_A - \frac{a}{g}\left[\frac{Q_P}{A_P} - \frac{Q_A}{A_A} - \frac{1}{2}(Q_P + Q_A)\left(\frac{1}{A_P} - \frac{1}{A_A}\right)\right] \tag{3.23}$$

3.4 Regulator

Regulators are used in systems to govern different parts of a system, often to ensure stability. In general a regulator receives an input signal from a measurement made in the system. This signal is compared to a reference point. If there exist a deviation, the regulator changes a control variable to minimize the error. This happens continuously. There are different kinds of regulators, but most common are presented in the form of serial PID regulators [32, p.334], as seen in equation 3.24. P- or PI control functions are achieved as special cases of the PID controller:

$$u(t) = \underbrace{K_p e(t)}_{\text{P-part}} + \underbrace{K_p T_d \frac{d}{dt} e(t)}_{\text{D-part}} + \underbrace{\frac{K_p}{T_i} \int_0^t e(\tau) d\tau}_{\text{I-part}} \tag{3.24}$$

$u(t)$ is the control variable that is sent from the regulator to the system, e is the deviation from the reference point and K_p, T_d and T_i are constants, deciding the characteristic of the regulator. Each of the three parts in a PID regulator has their own role.

The proportional term, the P-part increases or decreases the control variable proportional to the deviation. The problem with the P-part is that it is unable to reach zero deviation by itself. By adjusting the K_p the P-term controls the speed of the regulation, too high K_p leads to an unstable system. The D-term increases the control variable proportional to the change in time of the error term. This will contribute in a faster regulation and a dampening effect when the error term is decreasing. With a high value of the constant T_d oscillations will occur, and the system will reach instability. In addition to this the D-term has a tendency to increase the value of the noise in the system, and hence make it unstable. If there is much process measurement noise the derivative term should be dropped, this is done by setting $T_d = 0$ [33, p. 34]. One way of reducing the noise is implementing a filter. The filter is defined by a filter constant, T_f. In the time domain the derivative part can then be written as [31] [33]:

$$u_d = K_p T_d \frac{d}{dt} e(t) - T_f \frac{du_d}{dt} \tag{3.25}$$

The third term, the I-part, will increase as long as the error term is above set point and decrease as long as the error term is below set point. This means that the integral term will affect the control variable until the error is eliminated and the system is stable. The integral time, T_i, provides a stable system at the expense of quick regulation if it is high, but a low T_i will make it govern faster, but it might be unstable. If $T_i = \infty$ the I-term goes to zero and you are left with a PD-controller [33, p.33].

3.5 Turbines and generator

Using turbines and generators hydropower plants converts the potential and kinetic energy in water to electricity. The total hydraulic power, P_h produced can be estimated from the following relation:

$$P_h = \rho g Q H_0 \eta \tag{3.26}$$

Where ρ is the water density, H_0 is the total head, and η is the efficiency. Turbines can be divided into two types, the reaction turbine and the impulse turbine. The impulse turbine type has no pressure difference between inlet and outlet of the runner. All the specific energy converted to mechanical energy comes from the impulse forces created by the changes of direction of the velocity vectors.

In a reaction turbine type there is a pressure difference from inlet to outlet of the runner. At the runner inlet the specific energy is pressure energy. Through the runner the pressure drop is partly converted to mechanical energy by the flow. Among reaction turbines the Francis, the Kaplan and the Kaplan Bulb turbines are the most commonly used. Since the case powerplant Bratsberg has two francis turbines installed the following paragraph will focus on Francis turbines.

Francis turbines
Francis turbines are usually utilized for medium to high head power plants. It consists of spiral casing, guide vanes, runner and shaft. The spiral casing arrange for uniform flow distributed equally to the guide vanes. The guide vanes are the regulating component of the turbine, controlling the amount of water entering the runner. In the runner, the energy in from the water is converted to rotational energy led by the shaft to produce electricity in the generator. The efficieny of the turbine can be found from Eulers turbine equation [34]:

$$\eta_h = \frac{1}{gH_r}(c_{u1r}u_{1r} - c_{u2r}u_{2r}) \tag{3.27}$$

Where c is the absolute velocity and u is the peripheral velocity. Subscript 1, 2and u means inlet, outlet and tangential respectively.

Generator
A generator consist of a rotor and a stator. The rotor is transformed into an electromagnet by applying dc current to the rotor windings. When the shaft rotates the magnetic field created induces a three-phase set of voltages in stator windings. A torque produced in the generator, T_g, is felt as resistance by the turbine. This torque depends on the displacement angle δ. The displacement angle is the angle between the magnetic fields of the rotor and the stator. Maximum power from the generator occurs at $\delta = 90°$. The displacement angle must be seen in relation to the grid frequency. With a frequency of f = 50 Hz, as the nordic grid, the angular frequency, ω_{grid} will follow [35]:

$$\omega_{grid} = 2\pi f \tag{3.28}$$

In steady state operation the angular speed of the turbine is equal to the frequency of the grid. When there is a change in the load of the grid the displacement angle, δ, will change as seen in the relation [35]:

$$\frac{d\delta}{dt} = \frac{NP}{2}\omega_t - \omega_{grid} \tag{3.29}$$

Where NP is the number of pole-pairs in the stator and ω_t is the angular speed of the turbine.

3.5.1 Turbine model

In order to construct a simulation model describing the dynamic behaviour of the hydropower plant the turbine is essential, as it defines the system flow. The turbine model presented in this paper is suggested by Torbjørn Nielsen [35] [36] [37] [38]. The model uses Euler turbine equation, 3.27, to find two differential equations describing the flow and the angular speed of rotation[39]. From Eulers equation 3.27 it can be seen that the velocity of the guide vanes and at the outlet is important. Hence the guide vane angle and the runner blade inlet and outlet angle must be known as well as the angle of the guide vane at best efficiency point. That can be found from the main dimensions of the runner explained in *Pumper & Turbiner* by Hermod Brekke [34]. The two differential equations describing the momentum and the torque are presented below:

$$T_w\frac{d\tilde{q}}{dt} = h - (\frac{\tilde{q}}{\kappa})^2 - \sigma(\tilde{\omega}^2 - 1) \tag{3.30}$$

$$T_a\frac{d\tilde{\omega}}{dt} = \tilde{q}(m_s - \psi\tilde{\omega})\eta_h - \frac{T_g}{T_r} - R_m\tilde{\omega}^2 \tag{3.31}$$

The equations presented are on dimensionless form where the generator torque, T_g is dived by a rated value, and the head, the discharge and the rotational speed are all dimensionless and presented by:

$$h = \frac{H}{H_r} \quad \tilde{q} = \frac{Q}{Q_r} \quad \tilde{\omega} = \frac{\omega}{\omega_r} \tag{3.32}$$

The equations are taken from *Simulation model for Francis and Reversible Pump Turbines* so all constants and more details regarding the equations can be found there [39] . A short description of the variables and constants follows. T_w and T_a are time constants representing the hydraulic and rotating inertia. T_w is usually between 0.1 and 0.2 seconds, and T_a for large hydraulic machines are usually between 5 and 8 seconds [40]. κ is the opening degree of the turbine, σ represent the dimensionless self governing of the turbine and is dependent of the runner geometry. m_s is the dimensionless starting torque, defines as $m_s = t_s/t_r$, where t_s is the specific torque when the angular speed of rotation equals zero, and t_r is the rated specific starting torque. ψ is a machine constant describing pressure number, defined by velocity vectors at BEP.

For the simulations made for this thesis only the torque of the generator is relevant, so a simplified model where only the torque from the generator is important has been used [35]:

$$\frac{T_g}{T_r} = \frac{sin\,\delta}{sin\,\delta_r} \tag{3.33}$$

A frequency regulator suggested by Nielsen has succesfully been implemented to keep the torque from the turbine equal to the one from the generator, and hence keep the rotational speed constant. The PI regulator with permanent speed droop and servo motor time constant can in the time domain be described as [35]:

$$\frac{dc}{dt} = \frac{\kappa_{ref}}{T_K}\Big[-\frac{1}{\delta_t n_{ref}}\frac{dn}{dt} + \frac{1}{\delta_t T_d}\left(\frac{n_{ref}-n}{n_{ref}}\right) - \frac{(\delta_b T_K + \delta_t T_d)}{\delta_t T_d}c - \frac{\delta_b}{\delta_t T_d}(\kappa_{ref}-\kappa)\Big] \tag{3.34}$$

Where c, the speed of the servo motor is given by: $\frac{d\kappa}{dt} = c$. n is the speed of rotation, δ_t is the transient speed droop, δ_b is the permanent speed droop, T_d is the integration time and T_K is the servo motor time constant.

3.5.2 Connection with Method of Characteristics

The equations describing the dynamics and hydraulic response of the turbine, 3.30, 3.31, 3.34, is integrated into the rest of the power system using the MOC. The head felt by the turbine, H_t, is the available head given by the pressure in the pipe sections just before and just after the turbine element.

$$H_t = H_1 - H_2 \tag{3.35}$$

When the power plant is connected to the grid, the equation describing the torque from the generator is included as well.

3.6 Surging devices in HPPs

In hydropower plants a sudden change in power correlates with a sudden change in flow, this implies a pressure change in the piping system, also called water hammer. This pressure increase of a water hammer is due to the kinematic pressure of the water in motion and is proportional to the length divided by the cross sectional area of the pipe from the nearest free surface upstream of the turbine to the nearest free surface downstream the turbine. To minimize this pressure raise surging devices are installed. These surging devices provide a free water surface close to the turbine reducing the amount of water, and hence the pressure, building up in front of the turbine. The surging device will also improve stability in the system at a start-up, as the penstock can extract water from the shaft, allowing the water from the reservoir to accelerate slower [41]. Most commonly used is the surge shaft and the air cushion chamber(ACC), both shown i figure 7.

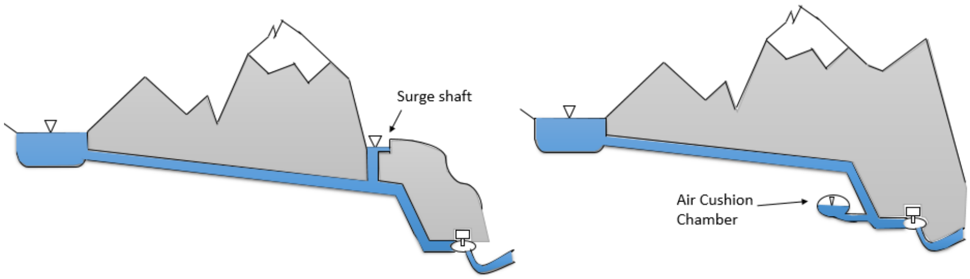


Figure 7: Surge shaft and surge chamber

Open surge tanks: The surge shaft is an example of an open surge tank. A shaft is connected to the headrace tunnel extended over the reservoir pressure head. At the end of this shaft a free water surface is open to the atmospheric pressure, as seen in figure 7 . During a shut down, the pressure in front of the turbine and further up the pressure shaft will rise, due to the inertia of the water. Water from the reservoir will then flow into the surge shaft as long as the pressure there is lower than in the pressure shaft and the total force from the pressure and inertia of the water from the reservoir. As the water level in the surge shaft increases, so will the gravitational force from the water until it fully has counteracted the momentum from the water. But again because of the inertia in the water, this will be over the pressure head of the reservoir and the flow will oscillate between the reservoir and the surge shaft until it is fully dampened by the friction.

Closed surge tanks: In some hydropower plants the topography complicates building a surge shaft. A closed surge tank as an ACC is then a common alternative. ACC is a closed system consisting of a excavated volume filled with pressurized air or gas, as illustrated in figure 7. ACC provide the same quality to the system as a surge shaft, shorter response time at start up, and pressure decrease at shut downs with the following oscillations. A drawback compared to surge shafts is more maintenance due to air leakage if the rock quality is low. The thermodynamics is more complicated in the closed surge tank, usually it is described by the polytropic equation, 3.6, as described in the next section. A more precise approach is using the Rational Heat Transfer (RHT), accounting for volume change and heat transfer or even better the Modified Rational Heat Transfer (MRHT), both described in appendix B.

3.6.1 Connection with Method of Characteristics

In the Method of Characteristics, a surge shaft can be simulated as [29]:

$$H_P = H_A + \frac{Q_A}{A_s} dt \tag{3.36}$$

Where A_s is the area of the free water surface, and H_A is the pressure at the end of the pipe connected to the surge shaft.

When it comes to the ACC the inertia and friction within the ACC is neglected, and the gas is assumed to follow the reversible polytropic relation, 3.6. By introducing the integrated continuity equation, $dV = -Q$, the following relation describes the dynamics in an ACC[29, p.125]:

$$(H' + \bar{H} - z)\left[V - \triangle t \frac{Q + Q_0}{2}\right]^n = C \tag{3.37}$$

Where, H' is the gage pressure, $\bar{H}$ is the barometric pressure and z is the elevation relative to the coupling with the tailrace tunnel. Newtons method can be used to solve 3.37 and 3.9

simultaneously.

3.7 Compressors

There exist two general types of compressors, the positive displacement compressor and the dynamic compressor. The positive displacement compressor increases the pressure of gas by confinement within a closed space. Hence the flow is discontinuous and not suitable for high flow rates. The dynamic compressors increase the gas pressure by first imparting a velocity pressure by rotating blades called an impeller and then converting it to a static pressure by a diffuser. Dynamic compressors can be divided into axial and centrifugal compressors. The dynamic compressors will be further explained here, as they are assumed to be most relevant for ACUR LE.

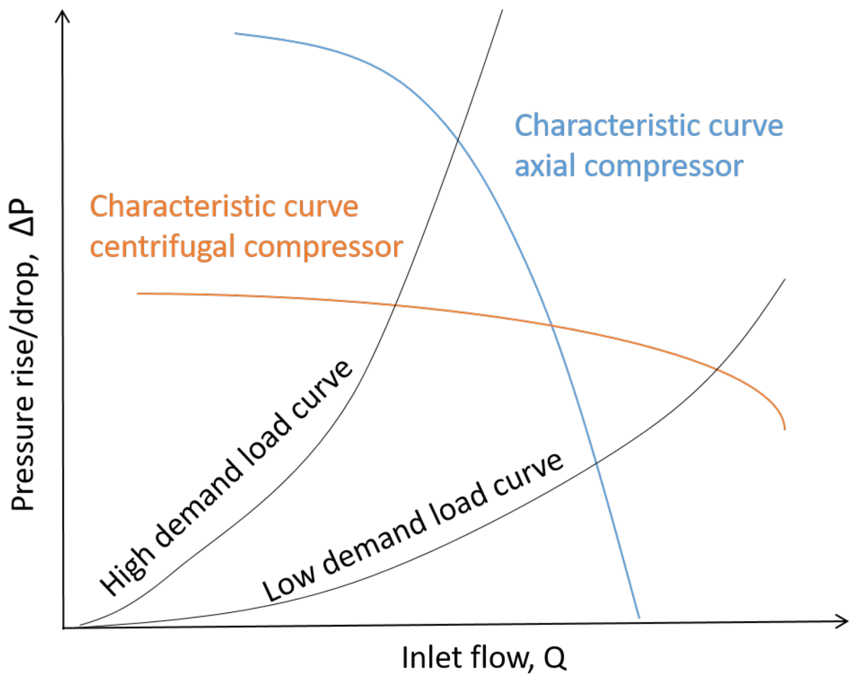


Figure 8: Typical characteristic curve for axial and radial compressor. Redrawn from McMillan [42].

Centrifugal compressors: In a centrifugal compressor the gas flows radially. With no internal losses the centrifugal compressor would produce constant pressure independent of the volume flow. This is not the case, as can be seen in figure 8. But the increase in volume flow is greater than the decrease in pressure, as the characteristic curve is relatively flat. This makes the centrifugal compressor suited to handle large volumes of gas at constant pressure and variable throughput control [42].

Axial compressors: Contrary to the flow in the centrifugal compressor, the gas in an axial compressor flows axially along the shaft. With no internal losses the axial compressor would produce constant volume flow independent of the the pressure, but as the figure 8 shows this is not happening. But as opposed to the centrifugal compressor the axial compressor characteristic curve is relatively steep, and the increase in pressure is greater than the decrease in volume flow. Hence the axial compressors are particularly suited for constant flow and variable pressure control. In general the axial compressor is better suited for higher flow and lower pressure discharge than the centrifugal compressor, as seen in figure 9.

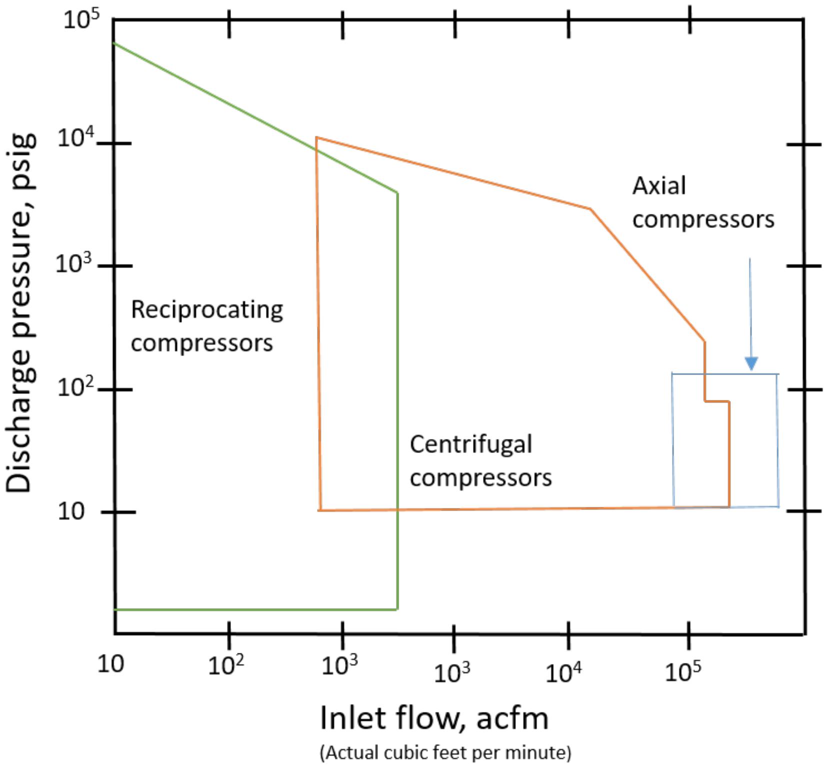


Figure 9: Typically operating ranges for different compressors. 1 psig=0.703 mWc and 100 acfm = 0.0472 m^3/s. Redrawn from McMillan [42] .

The characteristic curve for both the axial and the radial compressor depends on the suction operating conditions, vane position and speed. Example of a characteristic curve with efficiency curves for variable speed can be seen in figure 10. Parameters that can change the

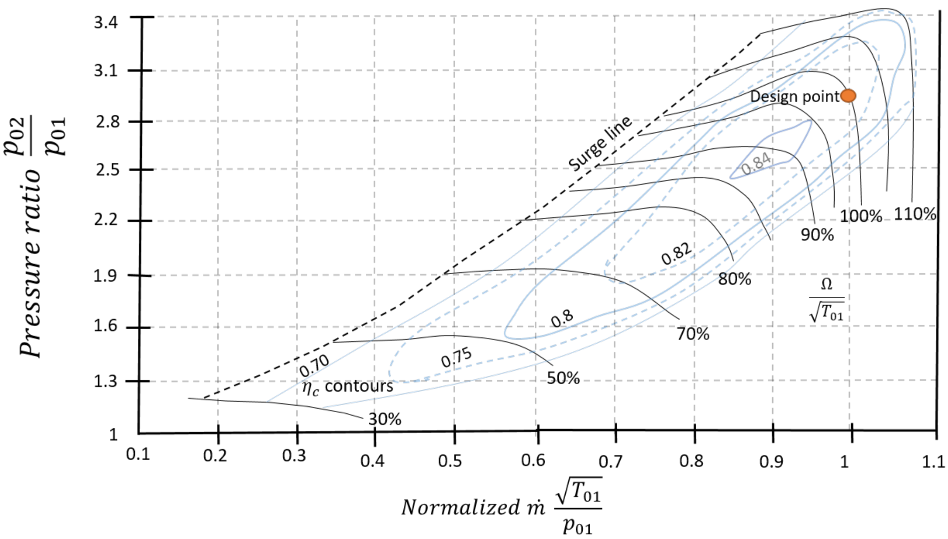


Figure 10: A customized characteristic map inspired by a characteristic map found in McMillan [42]

operating conditions for a compressor can be gas composition (molecular weight and specific heat), temperature and pressure at suction side [43, p.63]. All these variables can be adjusted to manipulate the position of the characteristic curve, but controlling the compressors are difficult due to dynamical aspects such as lags and delays.

Typically ways of controlling the throughput is discharge throttling, suction throttling, guide vane positioning and speed control. Discharge throttling is the least efficient as there will be high losses over the valve, and throttling the suction flow creates more and harder work for the compressor. Variable guide vane positioning creates the greatest turndown capability, hence arranges the widest operating range. Speed control can be calibrated to either flow or pressure control. By reducing the speed, the discharge flow and the pressure will decrease, and the operating point moves to a lower characteristic curve. For the speed controller, the power requirement is proportional to the speed raised to the second power if varying efficiency is neglected. For multistage compressors an operating line describes the off-design variation of

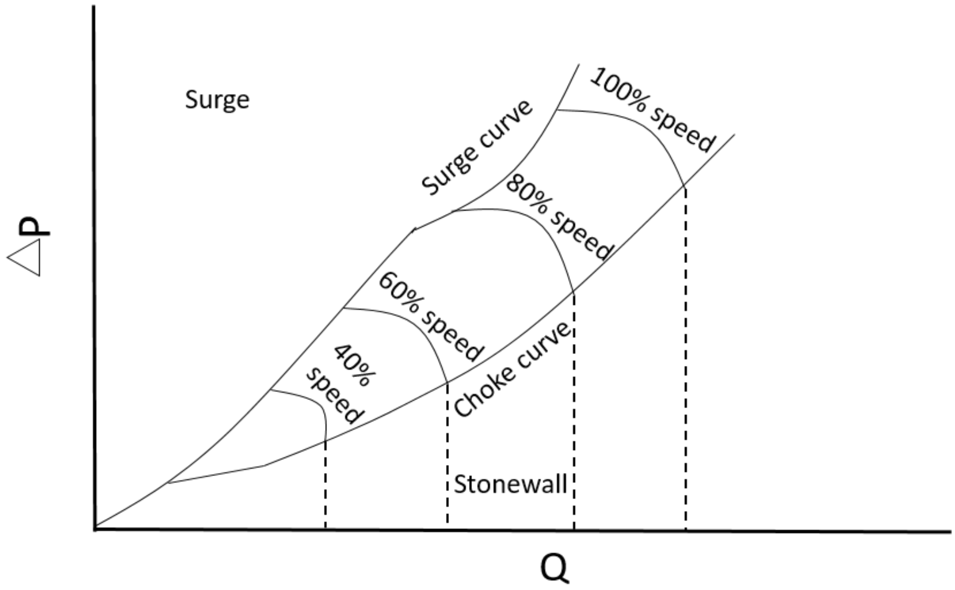


Figure 11: Characteristic curves, the surge curve and the choke curve for a variable speed multistage compressor. Redrawn from *Centrifugal and Axial Compressor Control* [42, p.52]

pressure ratio with nondimensional flow for a given exit configuration. The operating line should pass through the design operating point on the compressor characteristic curve. The working line for a compressor can be found if the exit configuration is known, this can be proven to be [44, p. 191]:

$$\frac{\dot{m}\sqrt{C_p T_{01}}}{D^2 p_{01}} = C\left(\frac{p_{0e}}{p_{01}}^{1-(\frac{k-1}{2k\eta_p})}\right) \tag{3.38}$$

Problems that can occur under contingently conditions are stall, surge and choke (stonewall). Stall happens as the flow through the compressor is reduced and the flow pattern becomes unstable. If the flow oscillates in localized regions around the rotor, the instability is called stall. Stall can further develop into an instability called surge, where there is flow oscillations around the whole rotor [42]. Furthermore if a compressor is operating at a high throughput and low pressure, stonewall will occur and the output temperature will increase drastically. The problem areas can be seen in figure 11. The surge curve intersects the point of zero slope on the characteristic curve, and the choke curve intersects the point of infinite slope.

The temperature rise of the air through the compressor depends on the pressure ratio and the polytropic efficiency, η_p, ass seen in the following relation [44, p.29]:

$$\frac{T_1}{T_2} = \left(\frac{p_2}{p_1}\right)^{(k-1)/\eta_p k} \tag{3.39}$$

3.8 Measuring Volume flow

Measuring high flow over large areas is difficult and is mainly used for efficiency tests in hydropower plants. Measurements used now are Winter-Kennedy and Acoustic Travel Time- clamp on, and the Gibson method. The Winter-Kennedy estimates the flow through the turbine by measuring the pressure difference on a radial line from the turbine center via the spiral case. This method can measure the turbine flow, but is incapable of measuring the flow downstream the turbine, hence not an option for ACUR LE [45, section 15.2]. The Acoustic Travel Time uses ultrasound and signal-analysis to estimate the flow. Utilising the fact that the propagation velocity of an acoustic (generally ultrasonic) wave and the flow velocity are summed vectorially [45, appendixJ]. This method require uniform flow without disturbances, and is therefore unfit for measurements for ACUR LE. The one most relevant for the ACUR LE, the pressure-time method, also called Gibson method, is based upon Newton's law and the derived laws of fluid mechanics. The differential pressure between two cross sections is measured during deceleration. Further more the discharge is calculated as seen in the equation below [46].

$$Q = \frac{A}{\rho L} \int_0^t (\triangle P + \xi) dt + q \tag{3.40}$$

where A is the cross-sectional area, L is the distance between the cross sections, $\triangle P$ i the differential pressure and ξ is the pressure loss due to friction, t is the time and q is the leakage loss through the turbine. The latter one is not relevant for measurements downstream the turbine. Modifications considering unsteady friction factor, temporal acceleration and upper integration limit of the standard time-pressure method is still ongoing, and looks promising [47] [46].

4 Building the model

The following chapter describes the procedure of building the simulation model with the ACUR LE element to show its potential. The progression on the ACUR LE element is described, as well as its associated compressor, bypass valve and regulator.

4.1 Waterway, Turbine and Generator

An illustration of the case power plant modelled can be seen in figure 12. The pipe to Kilvatnet was set aside, pipes and tunnels were built up as described in the theory chapter, with parameters collected from technical drawings. The calculation of surge shaft 2 can be seen in appendix A as well as parameters for all sections. The time increment, $\triangle t$ was defined by the shortest pipe element as described in section 3.3, the pressure propagation speed, a, is set to 1200 m/s, but has been adjusted in some pipes to keep the length correct and N as an integer.

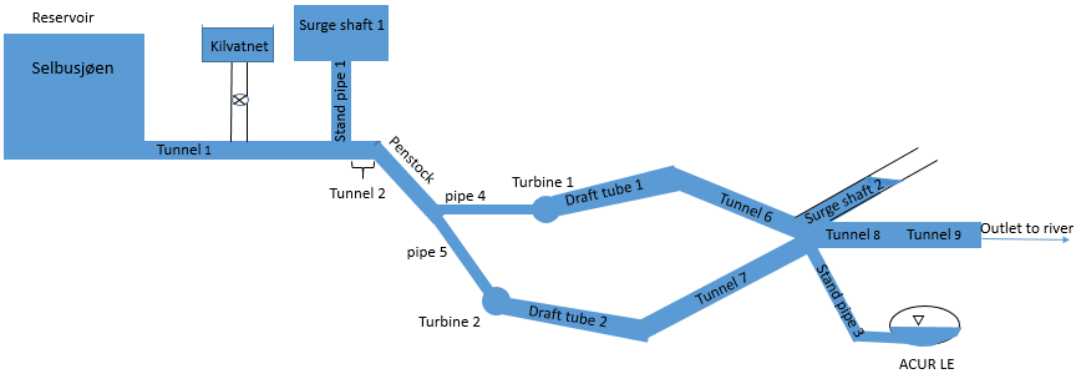


Figure 12: An illustration of the sections in the numerical model, not to scale.

The steady state water flow is calculated using equation 3.26, where g and ρ are $9.81 m/s^2$ and $1000 kg/m^3$ respectively. Nominal head is 130m, and the generator and turbine efficiency is assumed to be 0.988 and 0.96 respectively. Operating at best efficiency point at $P_{nom} = 56$MW for each turbine the nominal flow is found. Thereafter, head loss through every pipe section can be calculated by 3.2. With total head of 147 and 130 of these are taken out by the turbine, the rest must be lost in friction. The friction factor, f has been chosen between 0.03 for the penstock and 0.07 for the largest tunnels with low speed. All chosen to give an unite head loss similar to the actual loss through the system. To simulate the transient behaviour, the Method

	Turbine 1	Turbine 2
K_p	1.5	1.5
TK	0.1	0.1
T_d	5	5
bt	$1/K_p$	$1/K_p$
bb	-0.1	-0.05

Table 2: Parameters describing the governing of the turbines

of Characteristics is implemented. Utilizing equation 3.13 and 3.14 as described in section 3.3, the parameters B and R are decided. Further, head and flow are calculated for all internal points in each section by utilizing the equations 3.9 and 3.10. Finally the boundary conditions at the end and beginning of each section is calculated. The head of the first tunnel is set to always be equal to the head of the reservoir. The outlet to the river, the end of the pipe system the head is constant the head of the river, following equation 3.15. For junctions between pipes the boundary conditions is set by the equations 3.16, 3.17 and 3.18. Boundary conditions for surge shafts are found from equation 3.36, and for valves the boundary condition is found from equation 3.21. The draft tubes are simulated as expanding sections using equation 3.22 and 3.23.

From the nominal head and flow the dimensions and geometry of the turbines are calculated ass described in section 3.5.1. These values are used to find the remaining rated parameters for the turbine: T_w, σ, m_s, ψ. For the generator ω_{grid} is set to 50 Hz, NP is found from the calculations for the turbine dimensions, and ω_t is found by setting $d\delta/dt = 0$ in equation 3.29.

The PI regulator suggested by Nielsen, 3.34, is implemented with the parameters shown in table 2:

The behaviour of the servomotor was limited by a maximum speed of the guide vanes, $c = 0.1$:

$$c = \frac{d\kappa}{dt} \tag{4.1}$$

The equations describing the turbine(3.30 and 3.31) and generator behaviour,(3.33), as well as the governing equation (3.34), are solved simultaneous by a newton solver. The head and flow through the turbine is then inserted into the hydropower system by the MOC coupling equation, 3.35.

4.2 Elaboration of the ACUR LE

In Moens ACUR model the polytropic relation used in ACC is derived and the relation

$$pv^k = C_{specific} \tag{4.2}$$

where the specific volume, $v = V/m_{air}$, was found to be sufficient. It is stated in the example where this idea is taken from that this relationship is in accord with what MIGHT be measured[30, p. 64]. In addition to this the development of the temperature in the example is shown in a plot and is not constant. Hence the adiabatic assumption might not be satisfying, and considering the use of compressor temperature changes are likely to happen. As the author of this thesis is uncertain about the validity and accuracy of this model another model is suggested, where it is possible to change the temperature of the air. The new model is based on an example with an air-inlet valve described in *Fluid transients in systems*[29, p.130-132]. The general gas law for constant internal temperature, 3.5, is to be satisfied at the end of each time increment:

$$p\Big[V_0 + \triangle t\frac{-Q_{ACUR,0} - Q_{ACUR}}{2}\Big] = \Big[m_0 + \triangle t\frac{\dot{m}_0 + \dot{m}}{2}\Big]RT \tag{4.3}$$

where the subscript 0 means previous time step, and $\dot{m}$ is the mass flow in to ACUR LE, this will be a sum of the air going in or out of the valve and the air coming from the compressor. The air flowing through the valve depends on the pressure difference between the air inside the valve and the atmospheric pressure, as well as the absolute temperature. Four cases must be provided for[29, p.130]:

Subsonic air flow in

$$\dot{m} = C_{in}A_{in}\sqrt{7p_{atm}\rho_{atm}\Big[\Big(\frac{p}{p_{atm}}\Big)^{1.4286} - \Big(\frac{p}{p_{atm}}\Big)^{1.714}\Big]} \quad p_{atm} > p > 0.53p_{atm} \tag{4.4}$$

Critical flow in

$$\dot{m} = C_{in}A_{in}\frac{0.686p_{atm}}{\sqrt{RT_{atm}}} \quad p < 0.53p_{atm} \tag{4.5}$$

Subsonic air flow out

$$\dot{m} = -C_{out}A_{out}p\sqrt{\frac{7}{RT}\left[\left(\frac{p_{atm}}{p}\right)^{1.4286} - \left(\frac{p_{atm}}{p}\right)^{1.714}\right]} \quad \frac{p_{atm}}{0.53} > p > p_{atm} \tag{4.6}$$

Critical flow out

$$\dot{m} = -C_{out}A_{out}\frac{0.686p}{\sqrt{RT}} \quad p > \frac{p_{atm}}{0.53} \tag{4.7}$$

C_{in} and C_{out} is the valve discharge coefficient, ρ_{atm} is the density of atmospheric air and A is the area of the valve opening. In this model the discharge coefficient times the area of the valve opening has been combined to one variable, CA_valve as seen in the MATLAB code in appendix D.3.

In the example where these equations are derived from one of the assumptions is that the elevation of the liquid surface remains substantially constant, and the volume of air is small compared with the liquid volume of a pipeline reach. This is not correct for the ACUR LE case, so an extra equation considering the water level in the ACUR LE must be added.

$$L = L_{prev} - \triangle t\frac{Q_{ACUR,0} + Q_{ACUR}}{2A_{ACUR}} \tag{4.8}$$

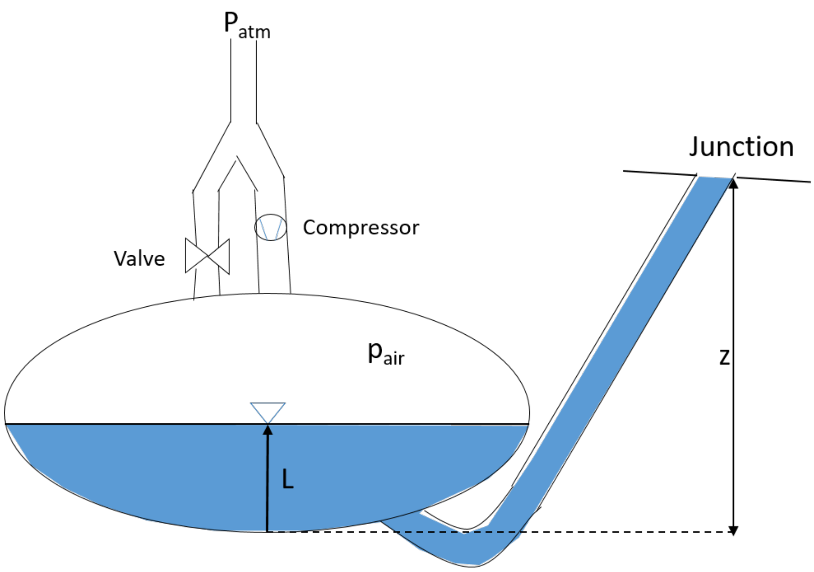


Figure 13: An illustration of the numerical setup for ACUR LE.

The relationship between the head at the bottom of ACUR LE, H $[mWc]$ and the pressure of the air, p [Pa] is:

$$\gamma(H - z_{ACUR} - L) = p \tag{4.9}$$

Where the specific weight is given by $\gamma = \rho_{water}g$ and z_{ACUR} represents the height of ACUR LE relative to junction where it is coupled with the rest of the hydropower, as can be seen in 13. By combining equation 4.3, 3.9, 4.9, and one of equations 4.4 to 4.7, depending on the pressure difference and the opening degree of the valve, the 4 unknown variables H_{ACUR}, $p_{air,ACUR}$, $\dot{m}_{valve}$ and Q_{ACUR} can be found. By assuming this relation between pressure, mass and flow, the following assumptions are made.

- The ideal gas model applies for the air.
- Air enters and leaves the pipe through the valve under isentropic flow conditions.
- The air mass within the ACUR element follows the isothermal law in that the mass is generally small and large areas of the ACUR LE and water surface provide heat capacity to hold the temperature close to the water.
- The water is incompressible.
- The air stored within the compressor or connected pipes is ignored.

The volume of ACUR LE was set to be 50 000 m^3, as Moen found it sufficient for the case power plant Bratsberg[9], and the elevation of the ACUR LE was set 30 meters below the junction coupling the ACUR LE to the tailrace tunnel. ACUR LE is initially filled with water and air. The initial water volume varies for each simulated case and can be seen in table 3. The code for initializing ACUR LE in MATLAB, can be seen in appendix D.1

	Volume of Water in ACUR LE [m^3]	**Percentage of total volume [%]**
Startup	3 000	6%
Shutdown	48 000	96%
Flood imitation	48 000	96%
Flood mitigation	3000	6%

Table 3: Water in ACUR LE initially for each case

First the ACUR element was implemented in the middle of the tailrace tunnel, between tunnel 8 and 9 on the pictorial schematic. This was problematic as there were fluctuations between the surge element(surge shaft 3) and the ACUR element in addition to the fluctuations between the discharge and the ACUR LE. Another position for the ACUR element was tried, placing it at the junction between tunnel 6, 7 and tunnel 8 on the pictorial schematic. This decreased the noise and improved the results, hence this setup was chosen.

4.3 The Regulator

This subsection describes the development of the regulator, the associated MATLAB-code for can be seen in appendix D.5. The regulator governing the compressor in the ACUR LE is modeled as a PID-regulator. First a setup was tried, where the I-part was excluded as long as Q_{set} was changing. However this did not improve the results so the PID-regulator was chosen to apply all the time. The input signal to the regulator is the discharge at the junction between tunnel 5, 6 and 8 compared to a set point. An accurate method for measuring the flow is still not available, but as the outcome of the Gibson method seems promising an accurate flow is used as input signal. The set point is at the beginning the current flow, and can be linearly increased or decreased depending on the case simulated. It is described by the following function:

$$Q_{set} = Q_{set,prev} + c\triangle t \tag{4.10}$$

where the constant c is the operational limitations of maximum rate of change, as described in section 2.5.The maximum rate of change in the discharge can be calculated for each case by the relation:

$$\dot{Q}_{max} = \frac{\triangle P}{\triangle t}\frac{Q_{max}}{P_{max}} = \frac{62MW}{6min60\frac{s}{min}}\frac{92.6\frac{m^3}{s}}{130MW} = 0.1227m^3/s^2 \tag{4.11}$$

Where $\triangle P$ and $\triangle t$ is the power and time from the restrictions in table 1. This gives the following rate of change in the discharge for the different cases.

	c Startup $[m^3/s^2]$	c Shutdown $[m^3/s^2]$
Outside Salmon season	0.118	0.118
Salmon season	0.0129	0.0085

Table 4: Restricted rate of change in the discharge to the river

The model made here assumes an accurate measurement of the flow. A time delay of 0.1 seconds has been implemented from the flow is measured until an output signal from the regulator is received by the compressor/valve.

The regulator parameters for the ACUR-regulator; K_p, T_i, T_d and T_f has been adjusted to give quick but stable response. By trial and error the regulator settings that was found to be most convenient was:

Parameter:	
K_p	40
T_i	200
T_d	60
T_f	10

Table 5: Regulator parameters

The control variable, $u(t)$, is multiplied with the compressors maximum throughput, hence the control variable should not exceed 1. To prevent this the error term is described as:

$$e = \frac{Q_{set} - Q}{Q_{nom}} \tag{4.12}$$

An extra term was added to the error term. The additional error term was:

$$e_{surge} = \frac{HP_{surge,ss} - HP_{surge,current}}{HP_{surge,ss}} \tag{4.13}$$

That part was the deviation of the current head in the surge chamber compared to steady state. This was added because the change in head there affects the discharge flow, and should therefore be compensated for. This was later eliminated as it just increased the noise and made the governing of the discharge more challenging. Values exceeding an absolute value of 1 for the control variable, is changed to ± 1. When it comes to the valve the maximum throughput is controlled by the area of the valve, which can be fitted for its case. The valve will operate in between fully open($\tau = 1$) and closed($\tau = 0$) following the relation given below:

$$\tau_{acur} = \tau_{acur,prev} + c_{valve}u(t) \tag{4.14}$$

where c_{valve} is the maximum speed of the valve, here limited by a full closure in 1 second. The opening speed is 30 times lower than the closing speed of the valve. This is to prevent too much air dissipation, as the air flows fast out and there is some delay from the regulator.

The regulator governs both the valve and the compressor, but the control variable will affect the compressor and the valve different. If the control variable goes to zero when the valve is open, the valve will still be open and air will continue to issue from ACUR LE decreasing the pressure. The compressor will be turned off and the throughput will be zero as the control variable goes to zero. This creates an extra challenge for the regulator. To solve that problem the valve will start to close if the control variable is decreasing despite the fact that it still is negative.

4.4 The compressor model

The compressor delivers masses of air into to the ACUR LE. Ideally the compressor would be characterized by the following:

- High maximum discharge of air.
- Quick response.
- Short start up and shut down.
- Wide range of discharge flows.
- Easy to control the throughput.
- Constant temperature identical to the temperature of air inside the ACUR LE.
- Precise measurement of throughput flow.

As explained in the theory some of this can hardly be obtained with varying operational conditions and problems related to the governing of compressors. The operational conditions will vary and the compressor in ACUR LE will be acted upon by the transient flow from the tailrace tunnel in the hydropower plant. This changing parameters(inlet temperature, specific heat and varying pressure in the ACUR LE) will influence the characteristic curve for the compressor as explained in the theory, (section 3.7). In addition to this, some start up delay must be taking into consideration and the problem with surge, stall and choke will limit the compressor. The surge pressure will be more or less constant. The temperature on the inlet air may vary depending of the season and probably some during the day, but will most likely be quite constant, as the air is trapped underground. Hence this compressor will operate at approximately constant surge conditions, but variable discharge conditions.

To make a correct model of a compressor a characteristic curve from the actual compressor should be available. As this has not been procured a simplified compressor model has been made. Only limited by a maximum throughput, a maximum rate of change, and as an input a delayed signal from the regulator. The maximum rate of change is set by 0.3 $\dot{m}_{max}$ in one second, as NTNU professor Lars Eirik Bakken alleged it would be possible to change the throughput from 100% to 50% with anti surge. The temperature in the ACUR LE was kept constant, and the temperature of the air coming through the compressor was set to be the same as the temperature of the air inside the ACUR.

As maximum water out of the ACUR LE will be $Q_{nom} \approx 92$, that volume of air will ideally be maximum throughput from the compressor. Since the air is compressible, maximum volume of the air coming from the compressor will vary depending on the pressure. This can be found by the ideal gas law. From simulations with a passive ACUR LE, the highest pressure obtained was 309.850 kPa and the lowest was 203.890 kPa, but with the valve, the lowest pressure possible will be atmospheric pressure, 101.325 kPa. This gives a pressure ratio of approximately 1:3. Assuming the compressor must be able to deliver maximum throughput at maximum pressure the maximum mass flow should be the following:

$$\dot{m}_{max} = \frac{\dot{V}_{air,max} p_{max}}{R_{air} T_{in}} = \frac{92 \frac{m^3}{s} 309850 Pa}{(287.058 \frac{J}{kgK})(288K)} = 354.7 kg/s \tag{4.15}$$

The highest maximum throughput from a compressor found by the author was an axial compressor from MAN Turbomachinery with maximum inlet flow of 25 450 $m^3/min = 424 m^3/s$ and maximum allowable pressure at 25 bar (approximately 2 500 000 Pa) [43]. This gives a mass flow at outlet at approximately:

$$\frac{101325 Pa 424 m^3/s}{287.058 \frac{J}{kgK} 288K} = 534 kg/s \tag{4.16}$$

This is more than the requirements both for the throughput and for the pressure ratio. The model does not take into consideration any delays in start up.

5 Results and discussion

Simulation results for four different scenarios, start, stop, flood imitation and flood mitigation will be presented in this section. Requirements for the compressor, valve and regulator are discussed, before an overall discussion of the model and the concept follows in section 5.5.

5.1 Startup

Under normal conditions Bratsberg uses 12 minutes from zero to full production. With ACUR LE offering 50 000 m^3 of storage volume it ensures an acceptable rate of change in the discharge to the river and the power production can increase instantly. Figure 14 shows the flow at different parts of the waterway downstream the turbines during start up. The simulations shows the first 25 minutes of a startup. The startup scenario shows that by using ACUR LE during startup, today's limitations for changes in the discharge are met, and still the time from zero to full power production is reduced from 720 seconds to approximately 59 seconds. This differs from

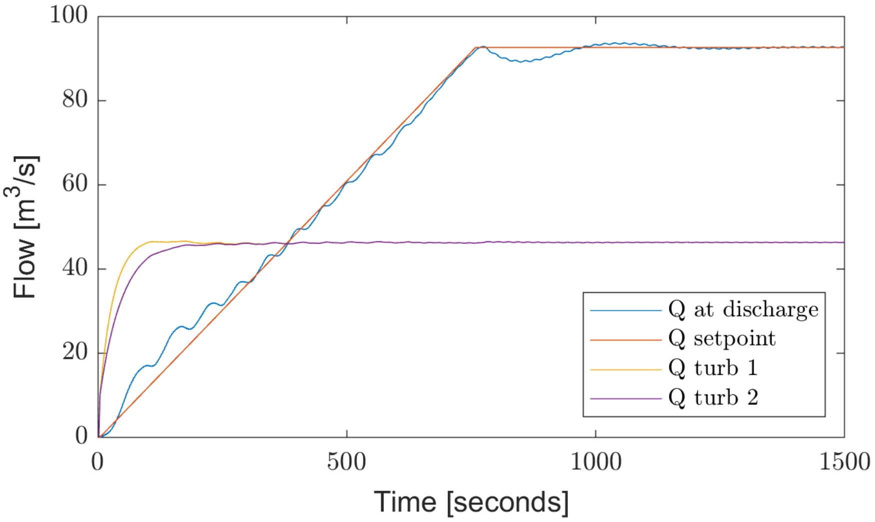


Figure 14: Flow through turbine, Q_{set} and discharge flow during startup, with measurements at the junction between the stand pipe coupled with the tailrace tunnel

the results Moen found in his thesis, with a start up in approximately 10 seconds [9, p.46]! The difference in result might be to different parameters describing the turbines, as the limiting part of the startup presented here seems to be the turbines, not ACUR LE. In addition to this the model used in this thesis has taken the surge element in the access tunnel into consideration, unlike Moen. From figure 14 it can be seen that the ACUR LE creates some fluctuations but they are small and diminish, hence the regulator seems to work as intended.

The simulations for start up are ran isolated and the compressor has been turned off. This is to prevent instability in the ACUR LE. As pressure fluctuations occur after transient behaviour in the water, the flow will naturally oscillate around Q_{set} before it stabilizes. With the compressor active, the regulator would have started the compressor if the control variable went beyond 0. With a control variable higher than zero the valve would open, and with delay in the regulator this would amplify the oscillations and instability could occur. This development of the instability will occur at the other scenarios as well and can be seen from a flood imitation in figure 23.

A second startup procedure was tested where the flow through the turbines was compared to the reference point. This would make the signal for changes in the flow coming from the turbines to reach the regulator faster, and hence prevent the high rate of change in the beginning. This

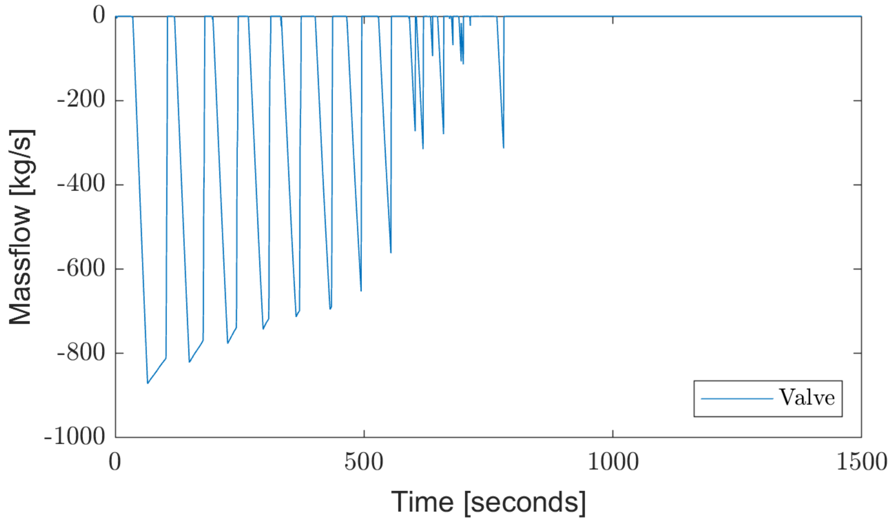


Figure 15: Mass flow through the valve during start up

however, turned out to be difficult as the measurements did not consider the water extracted by the ACUR LE.

The equations describing the mass flow of air through the valve, 4.4, 4.5, 4.6 and 4.7, uses a constant for the discharge coefficient but takes pressure difference into consideration, and a varying area. The expression used in this model uses the same discharge coefficient for flow in and out of the chamber, and a suitable dimension of the area times the discharge coefficient seemed to be 0.8. The discharge coefficient is hard to determine, but a value between 1.8 and 0.2 is normal[29, p.434]. By assuming the discharge coefficient being approximately 1 the area of the valve is 0.8 m^2. However, the plot in figure 15 shows the mass going through the valve enabling the ACUR LE to work as intended, and this can be used for requirements for the valve operation, independent of the accuracy in the discharge coefficient and the area of the valve in this model. From the plots of the mass flow through the bypass valve it can be seen that the maximum mass flow through the valve should be approximately 900 kg/s. The plot shows that the valve opens and closes many times, hence the flow through the valve is varying. With a less varying valve opening the requirements for maximum throughput might be lowered and close to the maximum mass flow found for the compressor. Then the regulator must be improved or the operation of the valve should be decided in advance.

As the highest flow of air out of the valve will be for the startup and the flood dampening scenario, this valve dimension times the discharge coefficient should be sufficient for all operational scenarios at this case power plant.

5.2 Shutdown

Outside salmon season shutting down the hydroelectric production today takes the same amount of time as starting it. With ACUR LE implemented simulations show that the shutdown time can be considerable reduced. Figure 16 shows different flows inside the waterway for a shutdown scenario. Shutdown at this case power plant shows that the time used to stop the turbines can be reduced from 12 minutes to approximately 2 minutes outside the salmon season, and still meet today's restrictions regarding discharge flow to the downstream river. For the shut down

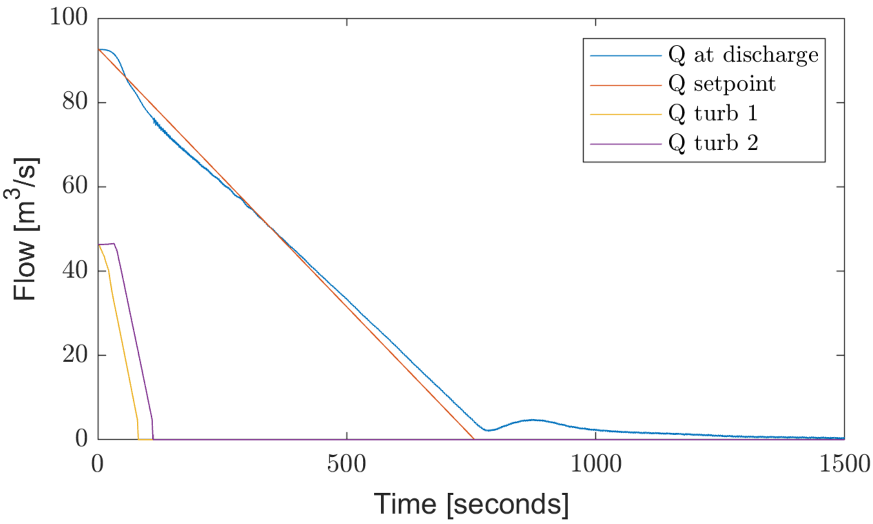


Figure 16: Flow through turbine, Q_{set} and discharge flow at shutdown$[m^3/s]$

scenario the reduction in time is higher in this thesis than in Moens that is mainly due to higher throughput of the turbine here, and that the limitations for rate of change in throughput from the compressor is higher here.

For the shutdown scenario the compressor is the most important component as it will be the limiting part of ACUR LE's ability to counteract the rapid change in discharge to the river. The compressor in this model is limited by a maximum throughput at 490 kg/s which seems to be satisfying. Figure 17 shows the working range of the compressor. This was from a simulation where ACUR LE worked as intended, hence this can be used as requirements for the compressor. The compressor works in the range of 0 to approximately 490 kg/second, with a pressure ratio between 1:2.5 and 1:4. Hence the initial guess of the pressure ratio of 1:3 taken form a surge chamber seems to correspond quite well with the results coming from the simulations with the implemented ACUR LE. Figure 17 can be used to tell how vulnerable the compressor is for surge, stall and stonewall. The plot shows that for the shutdown scenario the throughput varies a lot, but it is highest between 100 and 800 seconds after the turbines start closing. This very varying operation might not be realistic for a compressor, but the same applies here as for the valve. If the compressor can be operated more stable a lower maximum throughput might be sufficient, and the requirements for the regulation of the compressor can be lowered. With better regulation, with either less noise and disturbances or preselected operation for the compressor, the same mitigation of the rapid alterations should be obtained without so varying operations for the compressor.

The compressor seems be vulnerable to stonewall as the main working area with low throughput at the end of the simulation is at high pressure. When it comes to surge and stall this might be harder to avoid, due to the varying operation. No start-up delay for the compressor is considered but should be implemented to get a more realistic dynamic behaviour of the compressor.

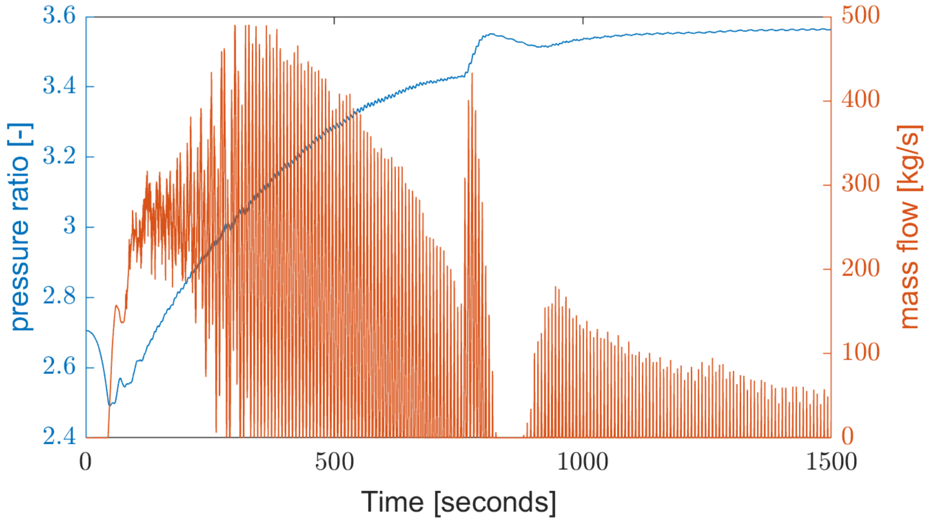


Figure 17: Mass flow through the compressor during shutdown scenario[kg/s]

When ordering a compressor, the customer specifies the requirements when it comes to throughput, pressure ratio, working range, speed, etc. The desirable maximum throughput from a compressor is high, so alternatives to one single compressor should be considered. One single compressor is not necessarily the best option, and a combination of compressors with varying start up delay and throughput can be an option. Compressors in series increases the pressure but keeps the volume flow constant and compressors in parallel keeps the pressure rise constant but increases the throughput. Hence more compressors in parallel would be desirable. The shutdown scenario is, as the startup scenario, simulated isolated and the valve is kept close through the whole simulation. The same problem occurs for the regulation here as it did at the start up scenario. With both the compressor and the valve active, the regulator opens the valve and start the compressor sequential as the control variable oscillates around zero. Hence instability quickly occurs.To prevent this increasing oscillations for shutdown scenarios the valve is closed through the whole simulation.

5.3 Flood imitation

For flood imitation the flow in a natural flood should be imitated. Since the author of this thesis has no such available, a simulation testing how the ACUR LE responds on a preselected discharge sequence is ran instead. As long as the regulation works satisfactory the ACUR LE can be used to imitate floods. The power plant runs at steady state, and the change in discharge is just due to utilization of the ACUR LE. Figure 18 shows the first flood imitation. Here the

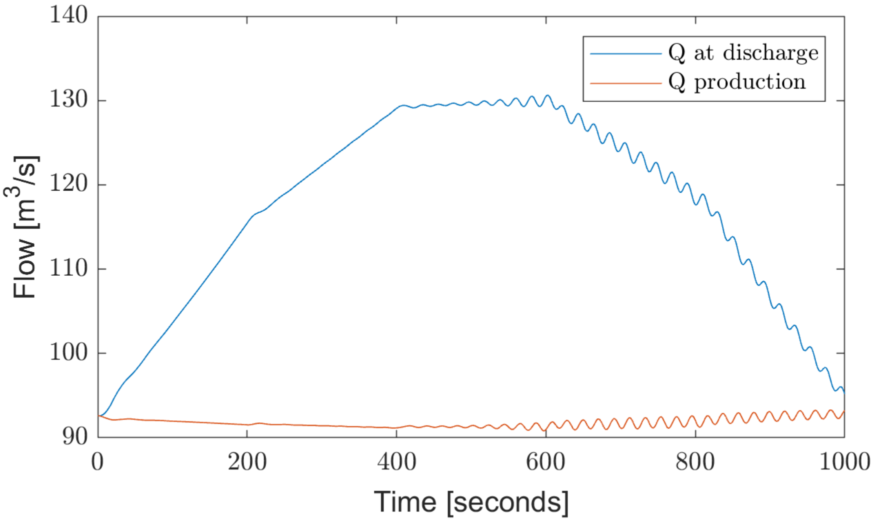


Figure 18: Discharge during flood imitation with a preselected Q_{set}.

Q_{set} was set up to increase the discharge flow from Q_{nom} at the beginning before decreasing again to nominal flow at the end. Some instabilities occur after approximatly 400 seconds, when the flood is flattening out. The oscillations comes from pressure fluctuations, but seems to not aggravate when the flood is decreasing. This is because the valve is closed. The compressor can only decrease the flow, by not compressing more air into the chamber.

A second method were tested, the result can be seen in figure 19. Here the control signal going to the compressor was preselected. The working area for the compressor for two different cases can be seen in figure 20. The thought was that this could prevent the varying compressor

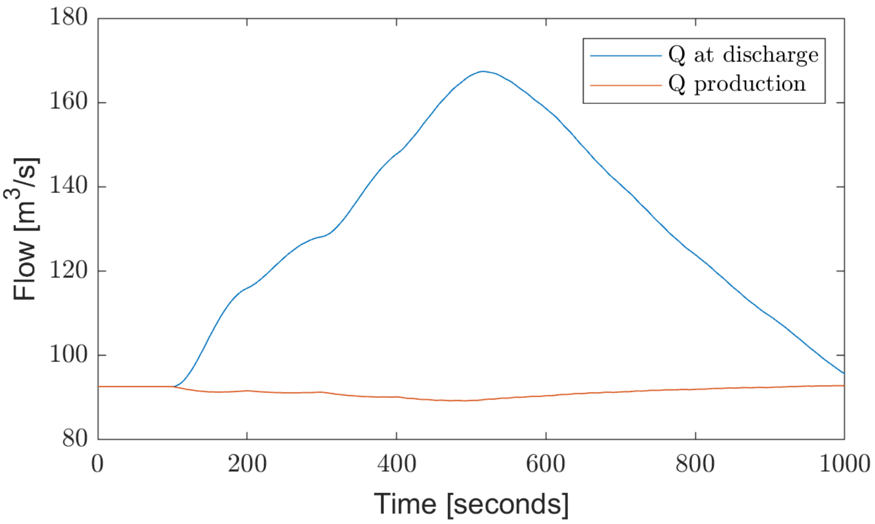
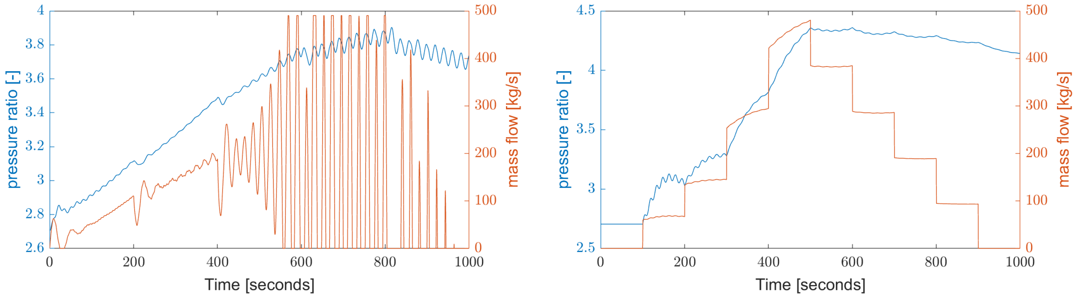


Figure 19: Flood imitation with a preselected step by step control variable for the compressor

operation, the small fluctuations and that operating the compressor at areas producing stall, surge and stonewall could be avoided. Figure 19 shows that the fluctuations in the flow is decreased, and the same oscillations do not occur. Figure 20 shows that the two different ways of regulating the compressor worked, but the preselected control variable avoided vary variable compressor work and decreased the oscillations. Hence it will most likely be easier to do with a real compressor. But the operational area for the compressor at the end of the simulation is with low throughput and high pressure, hence close to stonewall.



(a) Preselected Q_{set} (b) Preselected step by step control variable

Figure 20: Working area for compressor during flood imitation for the two scenarios

From the simulations it can be seen that the discharge flow to the river is independent of the flow through the turbines, and hence water stored in ACUR LE can be used to imitate natural flow variations.

5.4 Flood mitigation

In this simulation, ACUR LE was initially filled with 6% water, no hydroelectricity is produced at the power plant and the tailrace tunnel is used to extract water from the river filling up ACUR LE. The river is simulated as a constant pressure at outlet, hence variations in the river flow is not considered.

This simulation of water extraction can be seen in figure 21. The simulations shows that ACUR LE can extract water from the river as intended. The extraction works as intended for about 800 seconds. After around 900 seconds the chamber is almost full, hence the extraction from the river suspends. Figure 22b shows the height of water in ACUR LE. After about 900 seconds the height of water is close to 19 meters. Then the regulator starts to close the valve. The total height of the chamber is 21 meters.

Whether this extraction of water will have an impact on the damage from the flood depends on the size of the downstream river and its ability for self-governing. Small rivers with low self-regulation have smaller flood tops and the flow increase/decrease much faster there that in greater rivers. For cases like the one in Nidelva the effect of flood dampening will most likely be negligible, as there is high flow and a flood might last for days. The use of the valve and the opening degree of the valve can be seen in figure 22a. This scenario is like all others simulated

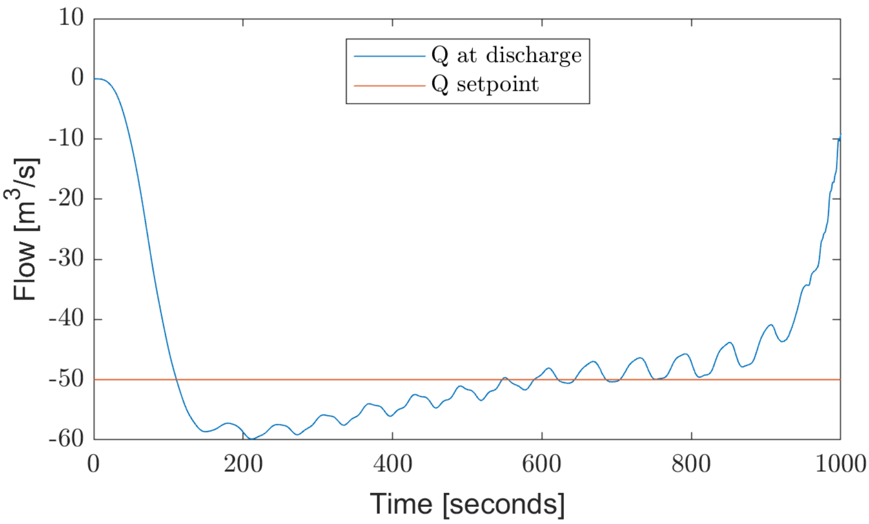
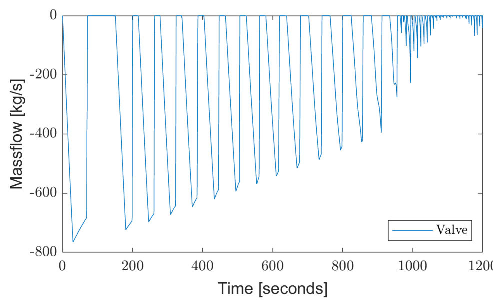
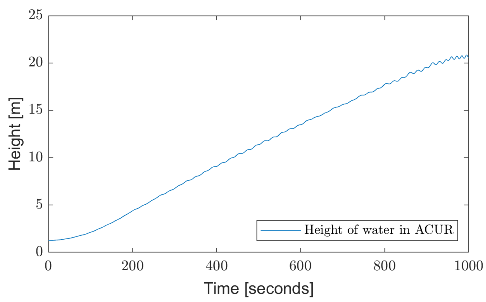


Figure 21: Flow showing water extraction from the river during a flood mitigation scenario.

isolated. This means that in real life, something will have to trigger the regulator to start the extraction of water. This could be triggered by a sudden increase in head at the outlet, by flow measurements in the river, or simply manually by a power plant employee. For this case the regulators task is mainly to close the valve when the ACUR LE starts to be full of water, or if the flood settles down.



(a) Mass flow through the valve during water extraction from the river



(b) The height of water in ACUR LE during water extraction from the river.

Figure 22: Valve operation and the filling of ACUR LE during flood mitigation

5.5 Superior discussion

5.5.1 Model evaluation

Unfortunately, the simulation results are unverified by laboratory experiments, and can therefore not be considered as anything more than plausible outcomes. The assumptions made during the development of the model are considered to be reasonable and will be further discussed in this section.

Some considerations regarding the use of the ideal gas law in substitution to the polytropic equation in the model for ACUR LE: Constant temperature, T, in the simulations is practically the polytropic equation, with $n = 1$. To get a more realistic model an expression for T need to be considered. For further development of the model the ideal gas would be preferable, as an expression for temperature can be carried out and give a more precise description of the dynamics in ACUR LE.

Isotherm behavior will give larger amplitudes in the water level, compared to the adiabatic behavior, but the pressure amplitudes will be lower with the isotherm in comparison to the adiabatic. The MRHT equation developed by Kaspar Vereide in his doctoral thesis is a more realistic model and a hybrid between the isothermal and the adiabatic model. As concluded in his thesis the adiabatic process was satisfying for the mass oscillations, but in this case the volume, mass and the temperature of the air will change as air will be furnished and extracted through the operation of the ACUR LE. Vereide also writes in his doctorial thesis: "*The heat transfer has a significant impact on the thermodynamic behavior of closed surge tanks for hydropower plants under two conditions; (1) slow transients with period longer than 20 minutes, and (2) transients where the start and end conditions differ*"[48]. Hence the heat transfer will probably have an impact on the thermodynamic behaviour in ACUR LE.

The air coming from the compressor will contribute in mixing the air and hence increase the heat transfer. This induces a complexity that eventually should be investigated in a CFD-analysis. Such an analysis will need a mature design of compressor dynamics and should therefore eventually be conducted at a later stage.

Another simplification made in this model is the measurement of the flow. There is still not a precise way to measure volume flows of this dimensions. If the development of the pressure-time measurement turns out to be accurate, the regulator can use flow as an input parameter, but if the measurement proves to be inaccurate, another input variable to the regulator must be considered.

The greatest uncertainty is the compressor. In this model very variable operation and throughput has been demanded. This might not be realistic for a real compressor. This will be discussed more in the next section.

5.5.2 Evaluation ACUR LE

As mentioned above, some assumptions were made to simplify the model. The simulations show a great potential for ACUR LE given that simplifications and assumptions are acceptable. The assumptions made are considering the compressor dynamic, measurement accuracy, thermodynamics and changing temperature of the air in the chamber, the flow through the valve, lags and delay in the regulator and the compressor. Summed up the greatest challenges seems to be:

- Accuracy of the measurements, both the discharge flow and the throughput from the compressor.
- Noise and delays in the measurements received by the regulator.
- Controlling the compressor.

There will most likely be a trade off between the gain in flexibility and the costs of this flexibility/ACUR LE, the costs will mainly depend on the compressor, as that seems to be the component with most variations in cost and performance.

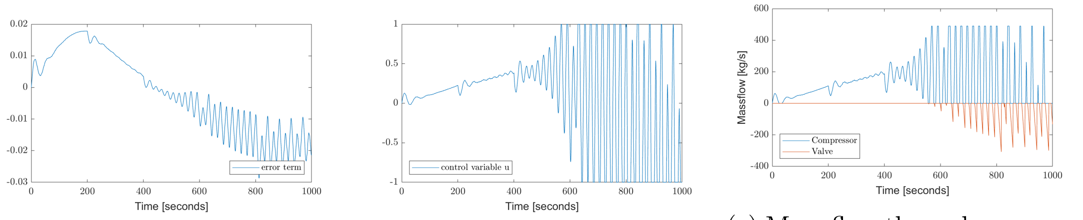
Compressor
The compressor model in this thesis is still very limited, and more of the compressor dynamics should be implemented in the model. Start up delay and delays at changing throughput is not put in to the simulations and will probably affect the results perceptible, as well as difficulties controlling the compressor throughput. When the compressor is regulated by measurements from the flow, transient pressure tends to disturb the regulator and demand highly varying throughput from the compressor. With the preselected compressor operation used to imitate natural flow variations this variations was avoided. The latter one seems better to lower the requirements for the compressor.

The expression for the temperature is maybe even more relevant and important to the compressor and its operating line, than for the thermodynamics in the excavated chamber. As mentioned in the theory, the operating line depends on the temperature, higher temperature gives lower flow at constant pressure. Figure 17 and 20 shows the compressor throughput with the associated pressure. From these figures it looks like the compressor vulnerable to both stonewall and surge/stall.

The compressor for ACUR LE must probably be specially designed for its destined power plant. Hence the exact compressor characteristic curve must be supplied by the manufacturer. A Characteristic map has been made for this case and can be seen in figure 10. A general characteristic map has been utilized and the actual values for the pressure ratio and the mass flow has been fitted to the requirements for this case. At the design operating point, the compressor rotates at 100% speed and has a stagnation pressure ratio of 3.6.

Accuracy in measurements
Some of the problems arising through this thesis is the noise to the regulator coming from the transient pressure. In addition to this the delay makes it difficult to make a stable system with quick response to unwanted changes in the discharge flow. Figure 23 shows a simulation where the compressor and the valve are active. The instability and the fluctuations are increased instead of dampened. In these simulations a delay of 0.1 second is used, but more might be expected.

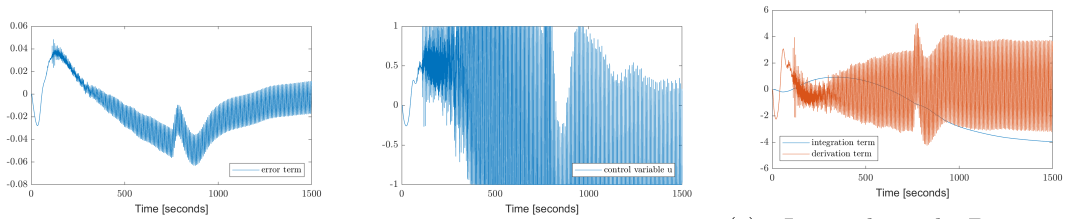
Governing and operating ACUR LE
Figure 23a shows the error term(24a), the control variable (24b), and the derivative and the integral term (24c). These figures shows the challenge coming from noise in the measurements. The filter at the derivative term dampens the noise substantially, but still the control variable



(a) Error term (b) Control variable (c) Mass flow through compressor and valve

Figure 23: Instabilities occurring during imitation with noise in the measurements and compressor and valve active

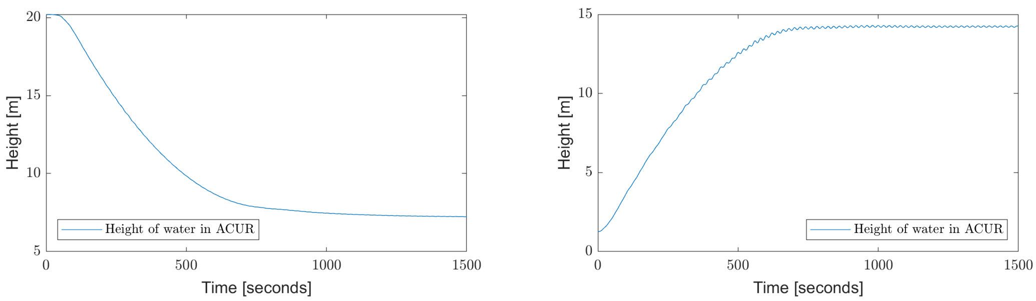
is varying. Figure 19 shows scenarios where the control variable has been set in advance. The preselected operating seems to work fine and might be a better alternative to some operational procedures, such as emergency stop, fast startups and flood imitation. It certainly reduces the variable compressor throughput and can be used to avoid certain damaging operational areas. The small fluctuations in the discharge that can be seen in figure 14 comes from transient pres-



(a) Error term (b) Control variable (c) Integral and Derivative term

Figure 24: Illustration of regulator parameters during shutdown

sure and are difficult to avoid. The downstream rivers has a capability to neutralize some of this smaller fluctuations, so they are acceptable and would come independent of the ACUR LE. The simulations ran in this thesis has been isolated scenarios, and there will be a challenge further to improve the regulator to find an optimal procedure for filling and emptying the ACUR depending on the operating conditions and what scenarios to expect. Start and stop has required different amount of water in ACUR at the beginning, as can be seen in figure 25 and filling/emptying the ACUR subsequent to simulated case has not been performed.



(a) shutdown (b) Startup

Figure 25: Height of water in ACUR LE during shutdown and startup.

The most difficulties and the highest demands from the compressor and valve are expected to be the shut down and start up with high alterations. Since the simulations indicates that these quick variations will be possible to mitigate, the optimal operational procedure should definitely be technological and physical feasible. The same applies for the strictest operational restrictions, the discharge limitations with a more gentle rate of change should be as feasible as the ones simulated here, just with modified dimensions of the excavated chamber. In these simulations the water never reaches the compressor or the valve, but a safety margin should be implemented to avoid drowning the compressor.

There will be a possibility to further optimize the regulator after commissioning of an eventual ACUR LE, based on learning from local and site-specific conditions. New information regarding the wanted discharge flow to the river can provide a better understanding of the optimal use of ACUR LE, and the regulation can be continuously improved just limited by the compressor(and the valve).

6 Conclusion

A 1D numerical model evolved to investigate the potential of ACUR LE has been made in MATLAB. Simulations ran for the case power plant Bratsberg confirms the potential of ACUR LE as a part of hydropower adapting to future energy systems with increased use of hydropeaking. In this thesis an access tunnel working as a surge chamber 120 meters downstream the turbine is implemented and differs from the model Moen used in his thesis, along with another way of modeling the dynamics of ACUR LE. But the results tally more or less with similar simulations run by Moen[9].

The scenarios startup, shutdown, flood imitation and flood mitigation have been simulated. Out of these four, ACUR LE seems to be most beneficial on the startup scenario where designed operating point was reached within 59 seconds, compared to 12 minutes as of today. The discharge to the downstream river is similar for both cases. Equivalently, the shutdown scenario is reduced to approximately 1/6 of today's 12 minutes. In addition to this ACUR LE can be used for flood imitation and successfully extract water from the river, mitigating flood peaks for smaller rivers.

The simulations made in this thesis confirm that a regulation of the discharge flow can be done successfully. ACUR LE has the ability to decouple the production flow and the discharge to the river, this makes it able to mitigate discharge fluctuation and increase operational flexibility of the hydropower plants. In addition to this the decoupling provides ACUR LE with the capacity to improve the river environment beyond the hydropeaking scenarios, by imitating natural flow variations or small flood peaks. This capacity can be continuously improved through optimizing of the regulator even after the physical parts of ACUR LE has been implemented.

For the case hydropower plant Bratsberg ACUR LE is proven to be beneficial given that the compressor, measurements and regulator can operate as the simulation model anticipates. A volume of 50 000 m^3 seemed to be sufficient for all cases except flood mitigation for this power plant. For rivers as big as Nidelva the dimensions of ACUR LE would be enormous to have an impact on the flood. Hence flood mitigation with ACUR LE will mainly be a bonus for smaller rivers, with less capability for self-regulation. A compressor for an ACUR LE at Bratsberg should have a maximum throughput at approximately 500 kg/s and a pressure ratio around 1:4. The varying throughput for the compressor makes it vulnerable for stall and surge. With a more stable operation of the compressor, this will be avoided, and the requirements for the maximum throughput can be lowered. The valve should be able to let almost 900 kg/s of air through at its maximum.

Lowering the requirements of the compressor, the regulator or the area of the excavated chamber would be possible but will be at the expense of the flexibility.

The simplifications made on the model are considered to be reasonable and can be used to specify requirements and demands for the different components in ACUR LE. The main uncertainty is attached to the compressors dynamics and the ability to control the throughput of the compressor, the accuracy of the measurements and the expression of the discharge coefficient for the valve.

7 Further work

The ACUR LE numerical model made in this thesis is based on several assumptions and simplifications leading to inaccuracy. Further work will be to improve the numerical model before building a physical model.

The compressor dynamics is the greatest uncertainty of the model, hence further investigation on compressor dynamic is necessary. This thesis has revealed some requirements that need to be covered in order to fulfill the purpose of the ACUR LE. Collaboration and a feasibility study with a compressor company would be desirable to examine the opportunities for either one compressor with required specifications or parallel coupling with several compressors.

An expression for the discharge coefficient at the valve should be developed, to get a more accurate understanding of governing the valve.

In order to make the regulator work as intended, accurate and precise measurements of the flow is essential, which is challenging for high flows with large flow area. This measurement uncertainty must be reduced or another way of regulation must be developed.

The regulator created in this thesis requires a Q_{set} in all scenarios except flood imitation where a preselected control variable varying through the simulated scenario was chosen. Another option would be to have a regulator that compares the rate of change in the discharge to a maximum rate of change, instead of a Q_{set}. In addition to accurate measurements the regulator must be fast to prevent even more delays for the compressor. A preselected operation for the compressor could be an option typically for the fastest shutdowns/emergency stops and fast startups. In 2017 *Energiteknikk* claimed digital twins would revolutionize the power industry. The author of this thesis suggests a similar twin to help regulate the compressor and valve in the ACUR LE. Digital twins are a virtual representation of physical assets entities and the connection between the virtual representation and the actual system is established by generating real time data using sensors. This might help the regulator evade problems as delay and noise in the measurements, and startup delays for the compressor could be omitted or at least reduced. More about how digital twin are used in hydropower can be found in *Energiteknikk* [49].

Investigation and CFD analyses on the thermodynamics would improve the dynamics of the chamber in the model. With the model suggested in this thesis an expression for the temperature of the air coming through the compressor should be developed. The modified heat transfer equations suggested by Vereide can be relevant to describe the heat transfer between the water, air and rock.

The intention of ACUR LE is to improve the operational flexibility of hydropower plants without increased negative environmental impact. This thesis focuses mainly on the technical solutions of the ACUR LE, but additional research on the river environment should be implemented in further development of ACUR LE. Research regarding optimal discharge flow, and information about the river and its natural flow, can give a better imitation of the natural flow. As the morphology, shape and light conditions are important parameters considering the biotic system in the river, this must be tuned for each different river where ACUR LE is to be implemented to give the best result. This is important to ensure ACUR LE will improve the ecosystem attached to the river. This however lays many steps ahead in the development of ACUR LE.

In addition to the technical feasibility the economical aspect must be considered. Forecast on energy prices and subdaily variations as well as the development of the compressor(s) and its requirements, the measuring instrument and the regulator will affect the profitability.

References

[1] *GECO 2019.* URL: https://www.iea.org/geco/ (visited on 05/04/2019).

[2] *Energy OECD Green Growth Studies Energy.* 2011.

[3] *The Paris Agreement | UNFCCC.* URL: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (visited on 05/04/2019).

[4] Enerdata. *After a 3-year stagnation, CO 2 emissions are on the rise again.* Tech. rep. 2018. URL: www.enerdata.net (visited on 05/04/2019).

[5] International Energy Agency. *Renewables.* URL: https://www.iea.org/geco/renewables/ (visited on 05/04/2019).

[6] Julian Friedrich Sauterleute and Julie Charmasson. "A computational tool for the characterisation of rapid fluctuations in flow and stage in rivers caused by hydropeaking". In: *Environmental Modelling and Software* (2014).

[7] IHA. *hydropwer status report.* Tech. rep. 2017. URL: www.hydropower.org (visited on 05/13/2019).

[8] Pål-Tore Storli. "A novel concept of increasing the flexibility at power plants with outlet to river". In: *HYDRO 2016, International Conference and Exhibition* (2016).

[9] Thomas Svensson Moen. "Mitigation of Discharge Fluctuations from Hydropower Plants by Active Measures". PhD thesis. NTNU, 2019.

[10] *Social Acceptance and Mitigation of Environmental Impact.* URL: https://www.h2020hydroflex.eu/work-packages/wp-5/ (visited on 05/13/2019).

[11] NVE. *Konsesjonsbehandling av vannkraft - NVE.* URL: https://www.nve.no/konsesjonssaker/konsesjonsbehandling-av-vannkraft/ (visited on 05/13/2019).

[12] NVE. *Vannkraftpotensialet - NVE.* URL: https://www.nve.no/energiforsyning/vannkraftpotensialet/ (visited on 05/13/2019).

[13] *Manually calculated from list provided by NVE.*

[14] Gudmund Bartnes, Jonas S Amundsen, and Ingrid B. Holm. *Kraftmarkedsanalyse 2018 - 2030.* Tech. rep. 84. NVE, 2018.

[15] N LeRoy Poff et al. *The Natural Flow Regime.* Tech. rep. 11. 1997, pp. 769–784.

[16] Julie K. H. Zimmerman et al. "Determining the Effects of Dams on subdaily variations in River Flows at a whole-basin scale". In: *River Research and Applications* (2010).

[17] W Gostner et al. "A holistic approach to reduce negative impacts of Hydropeaking". In: *Dams and Reservoirs under Changing Challenges* (2011).

[18] Angela H. Arthington. *Environmental Flows : Saving Rivers in the Third Millennium.* University of California Press, 2012, p. 422.

[19] Vegard Pedersen Sollien and Ole Kristian Berg. *Hydropeaking Effects on Riverine Benthic Invertebrate Fauna Composition and Drift.* Tech. rep.

[20] Ana Juárez et al. "Performance of A Two-Dimensional Hydraulic Model for the Evaluation of Stranding Areas and Characterization of Rapid Fluctuations in Hydropeaking Rivers". In: *Water* 11.2 (Jan. 2019), p. 201.

[21] S.J Saltveit et al. "Field Experiments on Stranding in Juvenile Atlantic Salmon(Salmo Salar) and Bown Trout (salmon Trutta) During Rapid Flow decreases caused by Hydropeaking". In: *Regulated Rivers: Research & Management* (2001).

[22] Roser Casas-Mulet, Svein Jakob Saltveit, and Knut Tore Alfredsen. "Hydrological and thermal effects of hydropeaking on early life stages of salmonids: A modelling approach for implementing mitigation strategies". In: *Science of the Total Environment* (2016).

[23] X.A. Yin, Z.F Yang, and G.E Petts. "Optimizing Environmental flows below Dams". In: *River Research and Applications* (2012).

[24] Emilie Person. "Impact of hydropeaking on fish and their habitat: Communication 55 (Laboratoire de constructions hydrauliques, Ecole polytechnique fédérale de Lausanne)". In: Communication (Laboratoire de constructions hydrauliques, Ecole polytechnique fédérale de Lausanne). 55 (2013).

[25] *Bratsberg | Statkraft*. URL: `https://www.statkraft.no/Energikilder/vaare-kraftverk/norge/Bratsberg/` (visited on 06/05/2019).

[26] NVE. *NVE kart Vannkraft utbygd og ikke utbygd*. URL: `https://temakart.nve.no/link/?link=vannkraft` (visited on 05/13/2019).

[27] Trondheim og omland fiskeadministrasjon (TOFA). *Nidelva - TOFA*. URL: `http://www.tofa.no/sider/tekst.asp?side=283` (visited on 05/13/2019).

[28] A. Yunus Cengel and M. John Cimbala. *Fluid Mechanics -Fundamentals and application*. McGraw-Hill, 2010.

[29] E. Benjamin Wylie and L. Victor Streeter. *Fluid transients in systems*. Prentice-Hall, 1993.

[30] Michael J. Moran and Howard N. Shapiro. *Engineering Thermodynamics*. Sixth. John Wiley & Sons, 2011.

[31] H. Anna Aftret. "Simulation and analysis of FCR operation of a Francis turbine". PhD thesis. NTNU, 2017.

[32] Jens G. Balchen, Trond Andresen, and Bjarne A. Foss. *Reguleringsteknikk*. 5th. Trondheim, 2003.

[33] Finn Haugen. *PID Control*. Trondheim: Tapir Academic Press, 2004.

[34] Hermod Brekke. *Pumper & Turbiner*. Vannkraftlaboratoriet NTNU, 2003.

[35] Torbjørn K. Nielsen. *Dynamic Behaviour of Governing Turbines Sharing the same Electrical Grid*. Tech. rep. NTNU, 1996.

[36] Torbjørn K. Nielsen. *Transient characteristics of high head Francis turbines*. Trondheim: NTNU, 1990.

[37] Pål Tore Storli and Torbjørn K. Nielsen. "Simulation and Discussion of Models for Hydraulic Francis Turbine Simulations". In: *IFAC-PapersOnLine* (2018).

[38] Finn O. Nielsen Torbjørn K. Rasmussen. "IAHRPaper92". In: *Analytic model for dynamic simulations of Francis turbines - implemented in MOC*. Sao Paulo: NTNU, 1992.

[39] Torbjørn K. Nielsen. "Simulation model for Francis and Reversible Pump Turbines Torbjørn". In: *11th asian International Conference on fluid machinery and 3rd fluid power Technology exihibition* x.x (2011), pp. 1–7.

[40] Torbjørn K. Nielsen. *Dynamisk dimensjonering av vannkraftverk*. Trondheim: SINTEF, Strømningsmaskiner, 1990.

[41] Odd Guttormsen. *TVM4165 Vannkraftverk og vassdragsteknikk, Vassdragsteknikk II*. NTNU, 2006.

[42] Gregory K. McMillan. *Centrifugal and Axial Compressor Control*. 2010.

[43] Tony J. Giampaolo. *Compressor Handbook: Principles and Practice*. The fairmont press, 2010.

[44] S.L Dixon and C.A Hall. *Fluid mechanics and Thermodynamics of Turbomachinery*. seventh. Elsevier, 2014.

[45] Bureau of Indian Standards. *IS/IEC 41 (1991): Field Acceptance Tests to Determine the Hydraulic Performance of Hydraulic Turbines, Storage Pumps and Pump Turbines*. Tech. rep.

[46] P.P. Jonsson, J. Ramdal, and M.J. Cervantes. "Development of the Gibson method—Unsteady friction". In: *Flow Measurement and Instrumentation* 23.1 (Mar. 2012), pp. 19–25.

[47] Georgiana Dunca et al. "Discharge Measurements using the pressure-time method: Different Evaluation Procedures". In: *U.P.B. Sci. Bull., Series D* 76 (2014).

[48] Kaspar V. Vereide. "Hydraulics and Thermodynamics of Closed Surge Tanks for Hydropower Plants". PhD thesis. NTNU, 2016.

[49] *Unik styring på Tonstad - Sira-Kvina kraftselskap*. 2018. URL: https://www.sirakvina.no/aktuelt/unik-styring-pa-tonstad-article395-859.html.

[50] Kaspar Vereide, Torbjørn Tekle, and Torbjørn Kristian Nielsen. "Thermodynamic Behavior and Heat Transfer in Closed Surge Tanks for Hydropower Plants". In: *Journal of Hydraulic Engineering* 141.6 (June 2015), p. 06015002.

[51] Frank P Incropera and David P DeWitt. *Fundamentals of heat and mass transfer*. sixth. New york: Wiley, 2007.

Appendices

A Parameters Bratsberg

Dimensions used in Bratsberg

The dimensions are primarily gotten from technical drawings, some parameters will probably differ from the exact values, but they are assumed not to affect the results. Especially the parameters downstream the turbine are aimed to be as correct as possible, as they are most important and relevant for this model. The technical drawings were not complete, so data related to a downstream surgeshaft has been provided from staff at Statkraft.

Pipe element	Length[m]	Cross section area [m^2]	Hydraulic diameter[m]
Tunnel 1	12 000	60	8.74
Tunnel 2	20		10.7
Penstock	135		7
Pipe 4 & 5	60		6.2
Tunnel 6 & 7	2 100	60	8.74
Tunnel 8 & 9	80		6
stand pipe 1	20		9
surge shaft 2		96.6	
standpipe 3	40		9
draft tube 1 & 2	40		$4 \rightarrow 6$*

Table 6: Parameters used in MATLAB. (*)linear increase D_{start} to D_{end}

Right after the draft tubes the tunnels for the sliding lock-gates work as stand pipes up to the access tunnel that works as a small surge shaft, these are so small that they have been neglected in this model, as they are assumed not to affect the accuracy of the simulations. An access tunnel 120 meter downstream the turbine has a cross sectional area of $25m^2$ and an elevation of 15%, and is working as a surge shaft. Assuming an approximately square tunnel, using Pythagoras gives a water surface area of 96.6 m^2, which is used as an area for the surge shaft simulated. An illustration of the surge shaft can be seen in illustration 26.

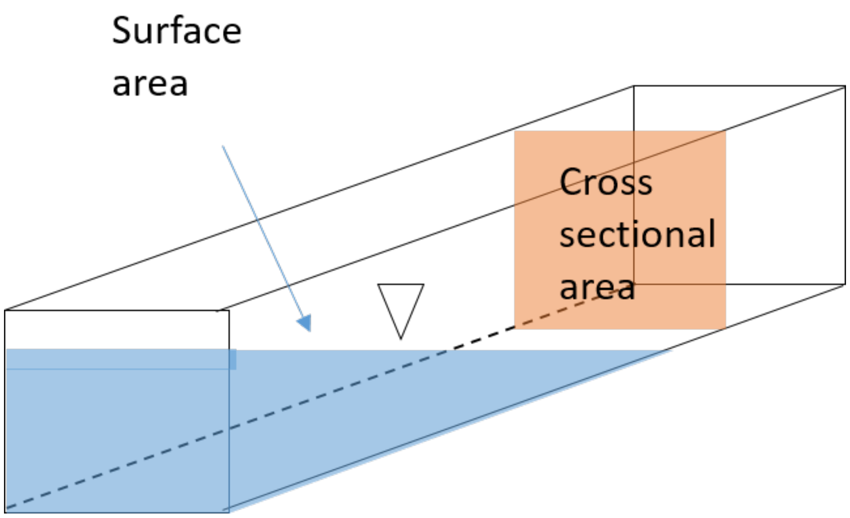


Figure 26: An illustration of the access tunnel, working as a surge shaft

B A modified rational heat transfer (MRHT)

There has been developed an method for describing the dynamics in a closed surge tank more accuratley than just by the polytropic relation, 3.6. Rational Heat Transfer (RHT) differentiate the equation for ideal gas making an expression for pressure change as a function of both volume change and heat transfer:

$$dp = \frac{1}{V}[-\kappa p dV + (\kappa - 1)dQ] \tag{B.1}$$

Where $\kappa = 1.4$ is the adiabatic constant, and dV and dQ is the volume change and heat transfer. This was first presented in 1968 by Graze, later Vereide improved the method to separate the heat transfer to air and water and calculation of the heat propagation in the rock [48]. The heat transfer in the Modified Rational Heat Transfer (MRHT) method[50]:

$$dQ = dQ_r + dQ_w \tag{B.2}$$

$$dQ_r = -h_r A_r (T_a - T_r) dt \tag{B.3}$$

$$dQ_w = -h_w A_w (T_a - T_w) \tag{B.4}$$

where subscripts a,w and r indicate air, water and rock respectively, h is the heat transfer coefficient, T is the temperature and A is the boundary surface. The heat transfer coefficients has has been calculated from Incropera and DeWitt[51]:

$$h_w = \frac{Nu_w \lambda_a}{L_w} \tag{B.5}$$

$$h_r = \frac{1}{\frac{1}{h_a} + R_r} \tag{B.6}$$

$$h_a = \frac{Nu_r \lambda_a}{L_r} \tag{B.7}$$

$$R_r = \frac{1}{\lambda_r} \tag{B.8}$$

where Nu, λ, R_r and l is the Nusselt number,thermal conductivity, heat transfer resistance and rock layer thickness respectively. The resulting model for heat transfer in closed surge tanks in the MRHT method becomes:

$$dQ = \frac{Nu_w \lambda_a}{L_w} A_w (T_a - T_w) dt + \frac{1}{\frac{L_r}{Nu_r \lambda_a} + R_r} A_r (T_a - T_r) dt \tag{B.9}$$

Where the Nusselt number is the only unknown and must be determined form laboratory experiments, field measurements, or empirical relationship. Following relationship was suggested for turbulent air flow by Incropera and Dewitt:

$$Nu = k\sqrt[3]{PrGr} \tag{B.10}$$

where k is an empirical constant, the Prantl number is $Pr = c_p \mu / \lambda$, where μ is the dynamic viscosity of the fluid, and finally the Gr is the Grashof number.

C Master's Agreement

1. Literature study on system dynamics and simulations of hydraulic transients in hydropower plants

2. Development of a numerical model for Bratset powerplant where simulations with and without ACUR can be performed

3. Implement a compressor model and the governing of this to be able to operate ACUR as intended

4. Simulate a selection of operational cases where ACUR is assumed to be beneficial

5. If the student will go to Nepal for an excursion, earlier and further work will be presented as a publication and presented at the conference; 9th International symposium on Current Research in Hydropower Technologies (CRHT-IX) at Kathmandu University.

D MATLAB script for some main elements

D.1 Initialize ACUR LE

```
function [V_tot,D,A,H_river,Water_acur,z,H_atm,L,V_w,V_air,HPair,
    p_air_acur,Temp,m]=ACURinitial(HPsp2)
global Nsp2 g rho start

V_tot=50000;
D=55;
A=pi*D^2/4;
R=8314/28.97; %specific gas const. for air
Temp=288;
z=-30;                    %relative to tailracetunnel
H_atm=10.329;             %[mWc]
H_river=6;

if start== 0
    Water_acur=0.96;
end

if start == 1
     Water_acur=0.06;
end

L=Water_acur*V_tot/A;      %water level
V_w=L*A;                   %volume water
V_air=V_tot-V_w;
HPair=HPsp2(1,end)-(L+z); %?

p_air_acur=(HPsp2(1,end)-(z+L))*rho*g;
m=p_air_acur*V_air/(R*Temp);
```

D.2 Equations ACUR closed valve

```
%ACUR closed valve
function EQ_acur = equationsACUR(x)

        global  V_air_acur QPacur Nsp2 mdot m z_acur...
                HPsp2 QPsp2 Bsp2 Rsp2 dt t Temp L_acur A_acur...
                mdot_comp

        Cp = HPsp2(t-1,Nsp2)+Bsp2*QPsp2(t-1,Nsp2);
        Bp = Bsp2+Rsp2*abs(QPsp2(t-1,Nsp2));

        V_airprev=V_air_acur(t-1);
        QPacurprev=QPacur(t-1);
        mdotprev=mdot(t-1);
        mprev=m(t-1);
        gamma=9810;      %specific weight water
        R=8314/28.97;


        %x(1)=p_air;      x(2)=HPacur;      x(3)=QPacur    x(4)=L
        EQ_acur(1)=x(1)*(V_airprev+dt*((-QPacurprev-x(3)))/2)-(mprev+
            dt*((mdotprev+mdot_comp(t))/2))*R*Temp;
        EQ_acur(2)=x(2)-Cp+Bp*x(3);
        EQ_acur(3)=gamma*(x(2)-z_acur-x(4))-x(1);
        EQ_acur(4)=x(4)-L_acur(t-1)-dt*(QPacurprev+x(3))/(2*A_acur)  ;
                  %Uttrykk for L
```

D.3 Equations ACUR open valve

```
%ACUR LE with open valve

function EQ_acur = equationsACUR_openvalve(x)

        global  V_air_acur QPacur Nsp2 mdot m z_acur...
                HPsp2 QPsp2 Bsp2 Rsp2 dt t Temp L_acur A_acur mdot_comp...
                alternativ tauAcur

        Cp = HPsp2(t-1,Nsp2)+Bsp2*QPsp2(t-1,Nsp2);
        Bp = Bsp2 +Rsp2*abs(QPsp2(t-1,Nsp2));

        V_airprev=V_air_acur(t-1);
        QPacurprev=QPacur(t-1);
        mdotprev=mdot(t-1);
        mprev=m(t-1);
        gamma=9810;     %specific weight water
        R=8314/28.97;
        CA_valve=tauAcur(t)*0.8; %Discharge coefficient*Area of open valve
        p_atm=101325;

        %x(1)=p_air      x(2)=HPacur      x(3)=QPacur    x(4)=L       x(5)=mdot_valve

        EQ_acur(1)=x(1)*(V_airprev+dt*(-QPacurprev-x(3)))-(mprev+dt*((mdotprev+(mdot_comp(t)+x(5)))/2))*R*Temp;
        EQ_acur(2)=x(2)-Cp+Bp*x(3);
        EQ_acur(3)=gamma*(x(2)-z_acur-x(4))-x(1);
        EQ_acur(4)=x(4)-L_acur(t-1)-dt*(QPacurprev+x(3))/(2*A_acur) ;    %Uttrykk for L

        if alternativ == 1 %subsonic air flow out
                EQ_acur(5)=-CA_valve*x(1)*sqrt((7/(R*Temp))*((p_atm/x(1))^1.4286-(p_atm/x(1))^1.714))-x(5);
        elseif alternativ == 2 %Critical flow out
                 EQ_acur(5)=-CA_valve*x(1)*0.686/sqrt(R*Temp)-x(5);
        elseif alternativ == 3 %Subsoniv air flow in
                EQ_acur(5)=CA_valve*sqrt((7*p_atm^2/(R*Temp))*((x(1)/p_atm)^1.4286-(x(1)/p_atm)^1.714))-x(5);
        elseif alternativ == 4 %Critical flow in
                EQ_acur(5)=CA_valve*0.686*p_atm/sqrt(R*Temp)-x(5);
        end
end
```

D.4 Equations Turbine

```
function EQT1 = equationsT1(x)
global sgT1 Tw1 dt qprev1 PsiT1 TtrT1 Ta1 omegaprev1 Rm1 md1 deltaprev1 polesT1 omegaref omegagrid deltarT1 bt1 Td1 kappaprev1 ...
    uiprev1 udprev1 alpha1rT1 ksiT1 beta1rT1 HC1 BH1 Qnom1 Hnom1 Rf1 Ra1 runaway1 Tgnom1 ngen1 epower1 t nref kapparef1 bb1 TK cprev1

% omegax=x1 qdimx=x2 deltax=x3 kappax=x4

% % %Turbine
    EQT1(1)=(HC1-(BH1*Qnom1*x(2)))-Hnom1*(((x(2)/x(4))^2) -(sgT1*(x(1)^2-1)))-(Tw1/dt)*(x(2)-qprev1);
    EQT1(2)=(x(2)*... %q
      (1-(((Rf1*x(2)^2)+(Ra1*(x(2)-(x(1)*((1+cot(alpha1rT1)*tan(beta1rT1))/(1+cot(asin(x(4)*sin(alpha1rT1)))*tan(beta1rT1)))))^2))/((HC1-(BH1*Qnom1*x(2)))/Hnom1)))*... %n_h
      ((ksiT1*(x(2)/x(4))*(cos(asin(x(4)*sin(alpha1rT1)))+tan(alpha1rT1)*sin(asin(x(4)*sin(alpha1rT1)))))... %m_s - dimensionless starting torque
      -PsiT1*x(1))... %Psi(pressure number)*omega
      -runaway1*(Tgnom1/TtrT1)*(sin(x(3))/sin(deltarT1))... %magnetic/generator torque
      -(Ta1/dt)*(x(1)-omegaprev1)... %acceleration
      -Rm1*x(1)^2); %R_m - mechanical loss
%Generator
    EQT1(3)=(polesT1/2)*x(1)*omegaref-omegagrid-(x(3)-deltaprev1)/dt;
%Power governor
   EQT1(4)=((((kapparef1/TK)*(-1/(bt1*nref)*(x(1)*omegaref-omegaref*omegaprev1)/(dt)+((nref-omegaref*omegaprev1*60/(2*pi))/(nref*bt1*Td1))...
   -(bb1*TK+bt1*Td1)*(x(4)-kappaprev1)/(bt1*Td1*dt)- bb1*(kapparef1-x(4))/(bt1*Td1)))*dt+cprev1)*dt+kappaprev1-x(4)); % governor equation
```

D.5 Regulator

```
function []=regulatorvalve()
%Regulator

global tauAcur u t alternativ V_air_acur Vtot_acur ui e dt p_air_acur ...
    Qset TCO start Qnom1 Qnom2 ud PID Q0 L_acur

maxdQ=(62/(6*60)*Q0/130);
T=dt*t;

%% u & e
Kp=40;
Ti=200;
Td=60;
p_atm=101325;
c_valve=0.0056; % closing in 1 sek
Tf=10;
bt=1/Kp;

e(t)=(Qset(t)-QP5(t-1,1))/(Qnom1+Qnom2);



    ui(t)=ui(t-1)+(Kp1/Ti)*0.5*(e(t)+e(t-1))*dt;
    ud(t)=(Tf1*ud(t-1)+(Td1/bt1)*(e(t)-e(t-1)))/(dt+Tf1);

    if t>1
        u(t)=(Kp1*e(t) + ui(t) + ud(t))*(V_air_acur(t-1)/(Vtot_acur*0.5));
    end

if u(t) > 1
    u(t) = 1;
elseif u(t) < -1
    u(t) = -1;
end

%Open valve
    % Q > Qset
if t>19
    if u(t-18)<0 % 0.1 delay
        tauAcur(t)=tauAcur(t-1)+c_valve*abs(u(t-18))/30; % /30 to slow down the opening
        if tauAcur(t)>1
            tauAcur(t)=1;
        elseif tauAcur(t) < 0
            tauAcur(t) = 0;
        end
    end
```

```
%Close valve
    %For lav Q
    if u(t-18)>0 || u(t-18) > u(t-19)
        tauAcur(t)=tauAcur(t-1)-c_valve*abs(u(t-18));
        if tauAcur(t)>1
            tauAcur(t)=1;
        elseif tauAcur(t) < 0
            tauAcur(t) = 0;
        end
    end
end

if L_acur(t) > 19.5
    tauAcur(t)=tauAcur(t-1)-c_valve;
     if tauAcur(t)>1
            tauAcur(t)=1;
        elseif tauAcur(t) < 0
            tauAcur(t) = 0;
     end
end

%cases
if p_air_acur(t-1) < p_atm/0.53 && p_air_acur(t-1) > p_atm
    alternativ=1; %Subsonic air flow out
elseif p_air_acur(t-1) > p_atm/0.53
    alternativ=2; %Critical flow out
elseif p_air_acur(t-1) < p_atm && p_air_acur(t-1) > 0.53*p_atm
    alternativ=3; %Subsonic air flow in
elseif p_air_acur(t-1) < 0.53*p_atm
    alternativ=4; %Critical flow in
else
    alternativ = 0; %OBSOBSOBS
end

 % tauAcur(t)=0; %Keep closed at shutdown
```

D.6 Compressor 1

```
function []=compressor()

global mdot_comp Temp p_air_acur u t dt start Time reg
R=8314/28.97;
T=dt*t;
p_atm=101325;

if T>0.1
    reg=u(t-18); % 0.1 seconds delay from measured sigganl to control
        signal is sent
else
    reg=0;
end

maxairflow=400; %[m^3/s]
mdot_max=p_air_acur(t-1)*maxairflow/(R*Temp); %massflow

maxdmdt=0.3*mdot_max/(180); % 180 = 1/dt => t*dt, change in one
    second
mdot_comp(t)=mdot_max*reg;

if mdot_comp(t)-mdot_comp(t-1) > maxdmdt
    mdot_comp(t)=mdot_comp(t-1)+maxdmdt;
end
if mdot_comp(t)-mdot_comp(t-1) < -maxdmdt
    mdot_comp(t)=mdot_comp(t-1)-maxdmdt;
end
if mdot_comp(t) < 0
    mdot_comp(t)=0;
end

% mdot_comp(t)=0; %if the compressor is turned off
```

E Paper presented at CRHT- IX

Simulation of a numerical model of ACUR LE

M Mestvedthagen

Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway

Abstract. The energy production in Europe is heading towards a green shift, adding more wind and solar energy to the power system. As power cannot be stored in the grid, these intermittent sources need balancing power to keep the power system stable. Hydropower plants are suited for this balancing task, but some have strict restrictions regarding the operation, due to river at the outlet. Rapid flow changes and discharge fluctuations will cause unacceptable environmental impact. By introducing a low energy, regulated air cushion chamber, ACUR LE, downstream, net flow into the river can be controlled and held within given restrictions, independent of the hydropower operation, thus making the hydropower plant more flexible.

ACUR LE is in the beginning of the Technological Readiness Level, TRL, and this paper presents the work on a second simulation model examining the technological feasibility of ACUR LE. The model presented is based on the reference power plant Bratsberg, made upon the Method of Characteristics and it is still work in progress. It presents a simplified numerical model for simulating hydropower plants with and without passive and active ACUR LE elements. The target is to implement an active ACUR LE with regulation.

1. Introduction

1.1. The green shift

With a growing energy demand and EUs goal to reach 20% of total energy consumption to come from renewable energy by 2020[2], the energy markets meet great challenges in the coming years. Wind and solar energy are the most expanding renewable energy sources with the same fundamental problem that they are intermittent and need additional energy sources to balance the power system[3]. The development for wind and solar energy will continue, and be doubled within 2030. This will lead to a power system more dependent on the weather and hence there will be need for more stabilizing power to the grid[5]. Hydropower has with more than hundred years of experience several advantages over most other sources of electrical power, including high efficiency, a high level of reliability, low operating and maintenance costs, proven technology, flexibility and in many cases; storage capacity.

1.2. Hydropower

Hydropower is the most flexible and consistent of the renewable energy sources, offering baseload capability, storage capability and grid stabilization by meeting peak and unexpected power demand. Flexible hydropower can play a major role in European energy objectives by enabling the increased penetration of intermittent renewables into the power grid [7]. Renewable energy represented 29.6% of the European energy mix in 2016, of which 10.7% came from hydropower. In Norway hydropower is by far the biggest power supplier with about 94% of the power production[12]. In 2018 the average annual production was calculated to be 134.9 TWh, this is about 62% of the impressive 212 TWh estimated hydropower potential in Norway[11]. Out of Norways 32.3 GW installed hydropower capacity, approximately 15% is storage plants with upper storage reservoir and outlet to river[1].

From a power production perspective, the water stored should be exploited in a way that maximizes the economic return. Norges Vassdrags- og Energidirektorat(NVE) (The Norwegian Water Resources and Energy Directorate), predicts increased price variation in the years to come. This gives storage hydro power plant with short response time an economic advantage[5]. In addition to mechanical restriction regarding power plant operation there will always be license restrictions limiting the flexibility to the power plant. License restrictions intends to limit the environmental impact. This is especially important for power plants in rivers or with outlet to rivers, as the power production directly affects the flow in the river. Highly varying power production leads to river flow fluctuations. To increase the operational flexibility, and hence the economic potential, for power plants with upper reservoir and outlet to river the discharge from the turbine must be decoupled from the discharge going into the river.

1.3. ACUR LE

Air Cushion Underground Reservoir (Low Energy), ACUR LE, intends to mitigate rapid fluctuations of the discharge flow to the down stream river by introducing a storage element for water between turbine and the outlet to the river. This is illustrated in figure 1. An excavated cavern connected to the tailrace tunnel works as a surge tank and a buffer-pool downstream the turbine. With a proper regulation this can make already existing power plants operate beyond todays limitations, hence making them more flexible. This idea was first presented by Storli in "A novel concept of increasing the flexibility at power plants with outlet to river" [9]. In Moen's master thesis "Mitigation of Discharge Fluctuations from Hydropower Plants by Active Measures" the concept has been further investigated in a numerical model with an implementation of a ACUR element to a power plant, with an associated regulation system [8].

Another important advantage for ACUR LE is the possibility for flood damping and imitating spring flood, illustrated in figure 2. ACUR LE can store water from the highest flood peaks, avoiding the most destructive parts of the flood, and release the water when the flood has settled. In rivers with hydropower developments, the absent

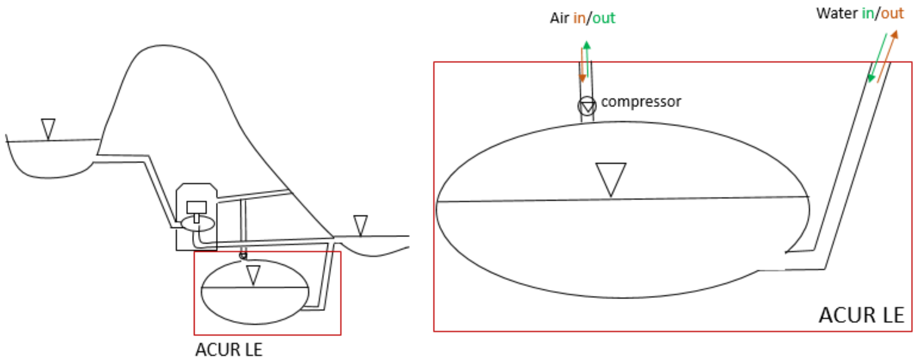


Figure 1: Principle of ACUR LE, not to scale. Redrawn from [9].

of spring flood influence the salmon spawn in a negative way. The ACUR LE can then be used to imitate the spring flood, by releasing large volumes of stored water.

The simulations made in Moen's thesis is made in LVTrans, this paper will present a first step model for a numerical solver in MATLAB. This work is in addition to Moen's master thesis a part of the first step on the way to provide proof-of-concept and to assess the technical feasibility of ACUR LE. The developement of ACUR LE is a part of the HydroFlex project, aiming to increase the value of hydropower by increasing the production flexibility[6].

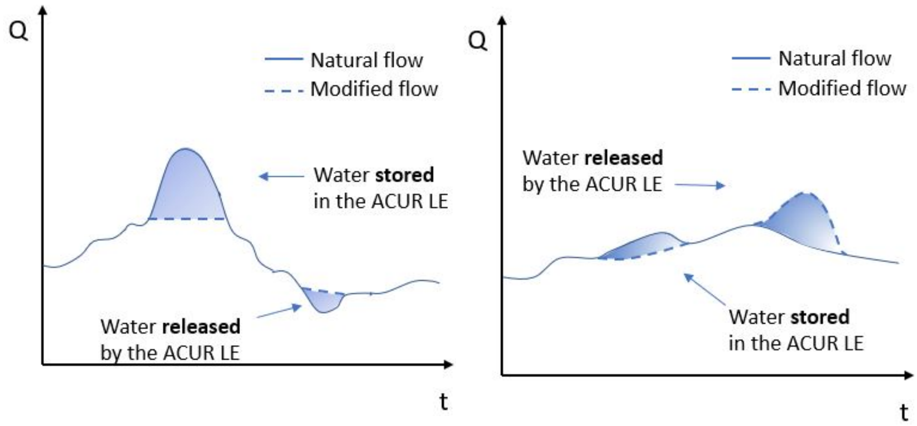
2. Theory

2.1. Hydropower in general

Hydropower utilizes the inexhaustible water cycle driven by the sun. Water has high density; hence a considerable amount of potential energy can be utilized from this continuous movement of water to generate electricity. The relation between power output, P_h, water flow(m^3/s) and head, H_0 (m) is given below:

$$P_h = \rho g Q H_0 \eta \tag{1}$$

Where ρ $(kg/m^3)$is the water density, g (m/s^2) the gravitational acceleration, Q (m^2/s) the water flow, H_0 (m) the head and η is the efficiency. For hydropower plants the total head is difficult to regulate, that means the change in production mainly is due to varying volume flow. Thus, for plants with outlet to river, variations in power production implies equivalent fluctuations in the flow into the river. This correlation is the one ACUR LE intends to reduce.



(a) Flood mitigation

(b) Flood imitation

Figure 2: ACUR LE operated to manipulate two different flood scenarios. Redrawn from Storli[9]

2.2. Method of Characteristics

The Method of Characteristics, MOC, is a well known method for modelling hydraulic systems in order to calculate dynamics. MOC is a numerical method for solving hyperbolic, partial differential equations(PDE)'s. Here the PDE's are the momentum equation and the continuity equation with the dependent variables velocity and hydraulic grade line elevation and the independent variables time and distance along the pipe. By using the MOC, these PDE's are transformed into two pair of Ordinary Differential Equations(ODE)'s, which can be integrated to yield finite difference equation and solved numerically. The method is explained more in detail in the book *Fluid Transients in systems* by Wylie and Streeter and equations for boundary conditions, pipes, junctions and valves can be found there[13].

3. The Method

3.1. Case Power Plant

In order to investigate the performance and evaluate the feasibility of ACUR LE, Bratsberg hydropower plant is used as a case for simulations. Bratsberg hydropower plant started producing energy in 1977 and is located in Trondheim, Norway. Two installed Francis turbines utilizes the 147 m net head from Selbusjen to together produce 124 MW at its maximum[8]. The average annual production is 650 GWh.
From Selbusjøen there is a 16 km long transmission tunnel discharging into Nidelva. An

Figure 3: Bratsberg power plant in Nea-Nidelvvassdraget. Screen-shot form map provided by NVE [10]

.

air cushion chamber is implemented just before the penstock. The reservoir, hydraulic conduits and position of the powerhouse cavern, as well the three other hydro power plants Leirfossen, Øvre Leirfossen and Nedre Leirfossen can be seen in figure.
The lower 8 km of Nidelva, from the sea upstream to the outlet of Bratsberg, is a well-known salmon river[7]. In the salmon season Bratsberg hydropower plant is allowed to reduce the power by 43MW/h[4]. This means that from a maximum production at 124MW it will take approximately 2.88 hours to shut down. The operating restrictions can be seen in table 1.

	Start-up [s]	Shut-down [s]
Salmon season	687	1038
Non salmon season	720	720
Technical restrictions	30	10

Table 1: Time spent to start-up and shut-down. $0 \rightarrow P_{max}$ and $P_{max} \rightarrow 0$.

3.2. The Model

Bratsberg was simplified and simulations were developed as a script in MATLAB using the Method of Characteristics. The model setup can be seen in figure 4.

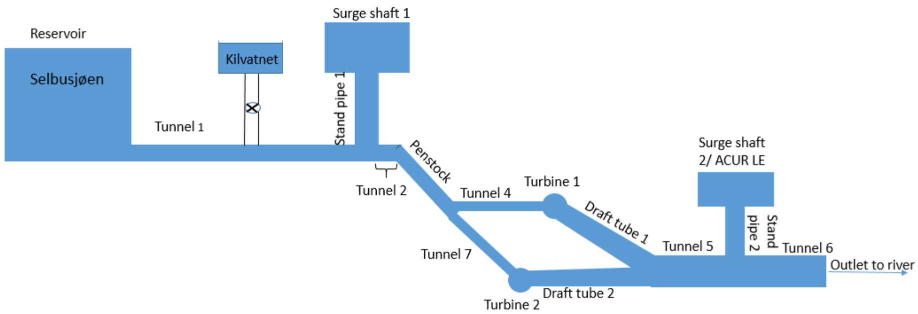
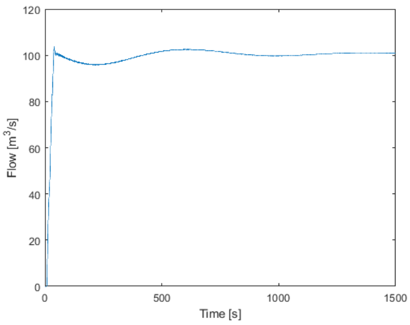


Figure 4: Simplified setup of Bratsberg used in MATLAB simulations

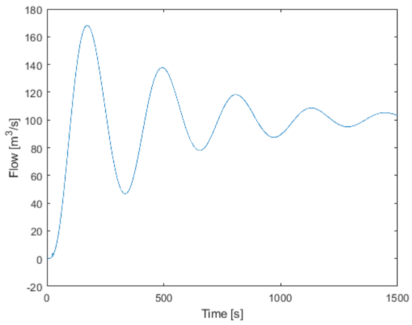
The tunnel to Kilvatnet was set aside and the air cushion chamber was modelled as a surge shaft. Turbines were simulated as valves with head loss corresponding to the actual turbines. As a first step of an ACUR LE element a surge shaft was implemented in the tailrace tunnel. Due to how the numerical solver works some of the lengths of the tunnels was adjusted, in order to achieve a whole number of pipe elements. The draft tube was modified to give stable results. Information regarding the nominal discharge differs, but calculations with a total efficiency of 0.86, head 147 m and 124 MW power gives approximately 100 m^3/s, which is the flow used. The goal is to simulate start up and shut-down with different start up and shut-down times with and without the passive ACUR LE elements. During the project different problems occurred and the model was limited to simulations of shorter periods of time, due to overwritten memory. The results presented in this paper are only a verification of the simulation model that will be used in further development of a ACUR-LE element with regulation and simulations with this element implemented.

4. Result and Discussion

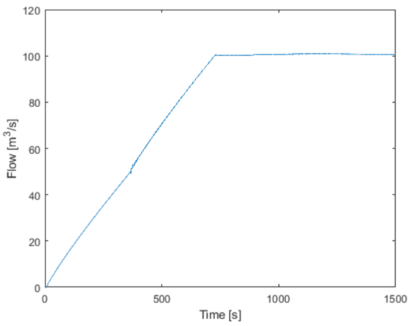
4.1. Start



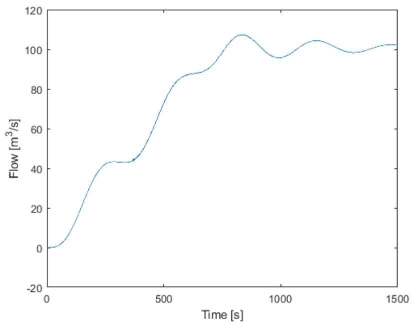
(a)



(b)



(c)



(d)

Figure 5: Discharge flow for start up different cases. $T_{start} = 30$ (a) and (b), $T_{start} = 720$ (c) and (d), with surge shaft/ACRU LE (b) and (d), without surge shaft/ACUR LE (a) and (c)

From the simulations based on todays limitations it can be seen that the power plant can hardly contribute in stabilizing the power grid immediately. With a startup time close to three hours the power plant works more like a base load with medium regulation capacity, and hence the economic potential with current price variation is unachievable. When it comes to the environmental impact it can be seen that there is a higher maximum discharge, and much more fluctuations in cases with the surge shaft, (5b and 5d), compared to the ones without the surge shaft, (5a and 5c). When it comes to the case with mechanical restrictions and no surge shaft, 5a, the rapid alteration is the problem, rather than the fluctuations.

4.2. Stop

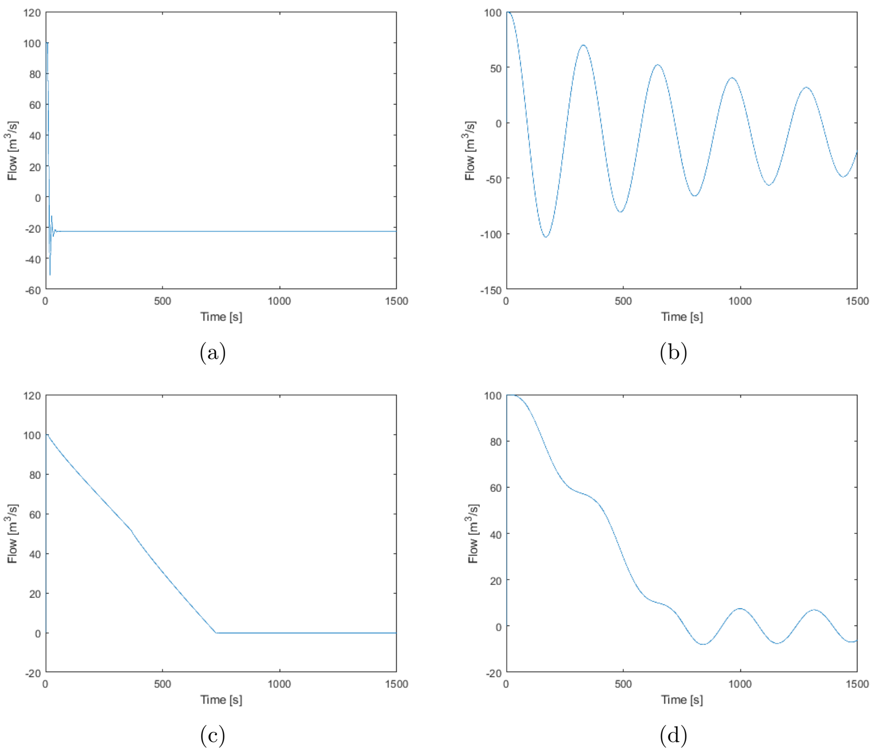


Figure 6: Discharge flow shut down for different cases. T_{close} = 30 (a) and (b), T_{close} = 720 (c) and (d), with surge shaft/ACRU LE (b) and (d), without surge shaft/ACUR LE (a) and (c)

It can be seen that a shut-down within todays limitations, fig 6c, gives small fluctuations in the discharge, compared to the fluctuations that can be seen with just the mechanical restrictions, fig 6a. For cases without the surge shaft in the tailrace tunnel rapid changes in the discharge flow is the problem for the river environments, rather than the fluctuations. From figure 6b and 6d it can be seen that the passive ACUR LE element seems to produce the reverse of the desired effect. Common for both start and stop the simulations shows that a passive element will not be enough to mitigate the fluctuations, it even aggravates the fluctuations. This corresponds to what Moen found in his work, but by implementing a regulation system ACUR LE became active and successfully mitigated the fluctuations [8].
With ACUR LE represented as a surge shaft, some problem arises. First of all, the

pressure on top will always be atmospheric, together with gravity this will make it impossible to increase the water height in the surge shaft over the outlet reservoir. Hence it will not be able to mitigate the fluctuations occurring at sudden shut-down. The possibility for regulation is limited as the use of pressure controlling the flow is impossible. A closed and active regulation system as the one described in Moen's thesis will be necessary. The model presented in this paper should be further developed to confirm the simulations in his thesis.

5. Conclusion

A simple model of a reference hydropower plant with an implemented surge shaft, as a simplified ACUR LE has been made in MATLAB. The surge shaft can hardly be called an ACUR LE as it is passive and actually aggravates the fluctuations. The simulations corresponds with theory about hydrodynamics and transient flow, and verifies that the physics in the model is quite correct. From the simulations made in this project it can be seen that the surge shaft produce the reverse of the desired effect without a regulations system. However, from Moen's work we can see that an active ACUR LE actually has the desired effect, and mitigates fluctuations. Which means hydropower plants with ACUR LE can be run more optimal for grid balancing and increased economic return. The MATLAB model must be further developed to see the potential of ACUR LE with an active system. Simulations regarding flood scenarios has not been done in MATLAB. From Moen's work the flood mitigation and imitation seems to run successfully[8].

6. Further Work

The model presented in this paper, examining the technological feasibility of ACUR LE needs further improvements. A more realistic turbine should be implemented. The main element, the passiv ACUR LE, should be replaced by an active ACUR LE element. Ideally as a closed system with regulation. The regulator must control a compressor or a pump, with the realistic limitations.

[1] Manually calculated from list from NVE.
[2] EU comission. 2020 climate energy package. Last accessed December 13, 2018.
[3] Eurostat. Renewable energy statistics. Last accessed December 13, 2018.
[4] Measured for Bratsberg received from Statkraft.
[5] J S Amundsen G Bartnes and I B Holm. Kraftmarkedsanalyse 2018 - 2030, 2018.
[6] HydroFlex. Social acceptance and mitigation of environmental impact, 2019. Last accessed March 11, 2019.
[7] International Hydropower Association IHA. Hydropower status report 2017, 2017.
[8] T S Moen. Mitigation of discharge fluctuations from hydropower plants by active measures. Master's thesis, NTNU, 2018.

[9] P-T Storli. A novel concept of increasing the flexibility at power plants with outlet to river. HYDRO 2016, *International Conference and Exhibition*, 2016.

[10] Norges vassdrags-og energidirektorat. Nve vannkraft utbygd og ikke utbygd, 2019. Last accessed March 11, 2019.

[11] Norges vassdrags-og energidirektorat. Vannkraft, 2019. Last accessed March 8, 2019.

[12] Norges vassdrags-og energidirektorat. Vannkraftpotensialet, 2019. Last accessed March 8, 2019.

[13] E. Benjamin Wylie and Victor L. Streeter. *Fluid Transientns in Systems*. Prenitce-Hall, 1993.

NTNU

Kunnskap for en bedre verden