University College of Southeast Norway

FMH606 Master's Thesis 2017
Process Technology

Simulation and control of hydro power plants

Valentyna Splavska

Faculty of Technology, Natural Sciences and Maritime Sciences

Campus Porsgrunn

University College of Southeast Norway

www.usn.no

Course:	FMH606 Master's Thesis 2017
Title:	*Simulation and control of hydro power plants*
Pages:	*67*
Keywords:	*hydropower system, modelling, Modelica, frequency and power control*

Student:	*Valentyna Splavska*
Supervisor:	*Bernt Lie*
External partner:	*Skagerak Energi*
Availability:	*Open*

Approved for archiving: _____

(Bernt Lie)

Summary:

Sustainable energy development implies meeting the energy needs of the future without jeopardizing the life quality of the planet. To achieve these goals is possible by gradually replacement in energy production profile of traditional energy sources by renewable until technically reasonable level. Hydropower is an undeniable leader among renewable energy sources and an important technological tool for implementation of Europe's ambitious climate and energy goals. This is proven by latest official reports and investigations. Inclusion into the grid of variable in time hydropower energy sources can cause distrubances. This impacts significantly to the quality of electricity and grid balancing. For generation profile prediction and control purpose, modeling of the hydropower systems is used. Since hydropower systems are principally similar and match well object-oriented modeling capabilities. The objective of this thesis is to develop mechanistic model of the hydropower system and to validate it. For this purpose, the mechanistic model based on the Euler equations was developed and tested by application to the case studies with different components configuration. For simplicity, the compressibility of water and elasticity of pipe walls were neglected, since the main aim is to compare a turbine model based on the Euler equations vs. a table look-up model. The influence of surge tanks on the transients of the system was illustrated. The developed model is not suitable for analysis of cavitation, because compressibility neglecting and filtering out of some pressure transients by elasticity in water/pipes. The research contributes in refining a case study for hydropower systems, and in emphasizing the usefulness of mechanistic turbine models. The results of model simulation were validated by comparison with "hill charts" model for relevant components configuration and empirical model consisting of look-up tables based on the turbine geometry obtained by using Alab software.

Preface

This work is an individual research task documented in a master's thesis FMH606 during the last (fourth) semester of the Master program Process technology at University College of Southeast Norway.

The topic of the master's thesis is "Simulation and control of hydropower plants". The development of the mechanistic model of the hydropower system based on the Euler equations and its validation stays in a focus in this thesis.

The task for the master's thesis (see Appendix A) is predominantly related to the courses FM1015 Modeling of Dynamic Systems and SCEV3215 Object-oriented Modeling of Hydro Power Systems taken in the first and third semesters of the master's program respectively. The working process on the task implied both application and amplification of the knowledge and skills obtained during entire masteræs program.

The obtained results of the work are supposed to present in a conference paper (58th International Conference of Scandinavian Simulation Society, SIMS 2017, Reykjavik, Iceland) (see Appendix B).

Acknowledgements

I am truly grateful to University College in Southeast of Norway for the excellent possibility to work on the task of master's thesis within simulation and control of hydro power systems. It was an incomparable opportunity to be involved into education process of the University College which gave me both theoretical knowledge and practical skills within modeling and simulation of dynamic systems, transport process and fundamental thermodynamic, process control techniques and other disciplines important for being the successful process engineer.

I want to express my deep gratitude to my supervisor Professor Bernt Lie for significant contribution to my research. The structural and systematical organization of weekly meetings with taste of coffee inspirated and encouraged me during this semester. Particularly, I would like to thank for course FM1015 Modeling of Dynamic Systems which has become a central factor in the decision making process of my future working field.

Contents

List of Figures

List of Figures

Nomenclature

Symbol	Explanation
IEA	International energy agency
IHA	International hydropower association
AS	Allmennaksjeselskap
NOK	Norwegian kroner
SIMS	Scandinavian Simulation Society
EPFL	École Politechnique Federale de Lausanne (Swiss Federal Institute of Technology in Lausanne)
IEEE	Institute of Electrical and Electronics Engineers
SIMSEN	Simulation software for the analysis of electrical power networks, adjustable speed drives and hydraulic systems
CFD	Computational fluid dynamics

1 Introduction

This chapter gives a brief preview of the thesis structure and content along with the background and goal of the work, and survey of available literature sources relevant to the master thesis' framework.

1.1 Background

In 2010, the European Commission defined the main idea of sustainable development as "meeting the needs of present generations without jeopardizing the ability of future generations to meet their own needs – in other words, a better quality of life for everyone, now and for generations to come" [1]. The last few years have witnessed positive intention and progress of the global society towards implementing targets of a new sustainable agenda and agreement on climate change. This process has stimulated interest in low-carbon, resilient and sustainable technologies and, hence, brought a particular focus on renewable and clean energy sources [2].

An undeniable leader among renewable energy sources has always been hydro power due to its several advantages. As the most conventional advantages can be mentioned: high level of reliability, proven technology, high efficiency, quite low operating, and maintenance costs, flexibility, and large storage capacity [3]. Nowadays over 97 % of the world's energy storage capacity relates to the hydropower sector [3].

Since 2005, due to new capacity additions, hydropower has been the absolute leader in electricity generation among renewable energy sources. Hydropower covers almost one-sixth of the world's electricity needs [4]. According to the Technology Roadmap prepared by IEA in 2012, hydropower is the major global electricity generation technology among renewable technologies. Moreover, hydropower technology will remain so for a long time as it is foreseen in [3]. In [3] it was predicted that by 2050 the global capacity approaches 2 000 GW and global electricity generation exceeds 7 000 TWh. Predominantly, increasing in hydroelectricity generation will be reached by realization of the large hydropower projects in emerging economies and developing countries. IEA in its latest report announced as the most perspective for hydropower technologies development regions in Africa (regional and cross-boundary river basins, including the Congo, Nile and Zambezi rivers), Asia (monstly in China) and Latin America (predominantly regions in Brazil) [3].

1 Introduction

At the end of 2015 world's hydropower generation reached the level of 3 975 TWh. By the results of 2015, the absolute leader besides of new installed hydropower capacity was China (19,4 GW). Countries with a significant contribution to the extension process of new installed hydropower capacity are Brazil (2,5 GW), Turkey (2,2 GW), India (1, 9 GW), Iran (1 GW) and Vietnam (1 GW) [2]. Information about added hydropower capacity generalized over continents is given in Appendix 1 figure C.2.

On the European continent Scandinavia and Alpine countries are pioneering and leading regions in the number of installed hydropower capacity. Here, the leadership position in hydropower sector development belongs to Norway (30 566 MW) [2, 5]. 99 % of all electrical power production in Norway originates from hydropower [4]. Also, Norway is Europe's absolute leader in installed hydropower capacity including pumped storage and remains on the 6th place in the global scale [2, 6]. Generalized picture over installed hydropower capacity in Europe is given in Appendix 2 C.4.

The development of renewable resources brings a new set of technological challenges not previously faced by the grid. Among these challenges, the variability of renewable generation has an urgent character [7]. The variability of renewable resources implicitly or explicitly depends on characteristic weather fluctuations. The weather forecast includes some part of prediction and uncertainty in itself, which, in its turn, induces uncertainty in generation output (on the scale of seconds, hours and days) and difficulties to predict it [7]. This contributes to disturbances which occur and can cause an unbalance of the grid system. If the part of renewable generation penetrations on the grid is considerably small (less than 30%), it can be smoothly integrated [7]. Otherwise, the application of modern approaches for extending and operating the grid is required.

The variability of renewable energy can be accommodated by using regulation scheme when demand and renewable supply are matched—both rising and falling together [7]. Nevertheless, the accommodation cost can rise dramatically if changes in demand and renewable supply occur in opposite directions.

Generation profile of hydropower sources has different variability profile as in case of wind power or solar renewable sources. It caused by the greater predictability (over wind power) of its generation even for run-of-river plants and the control over the source through its storage capabilities [7]. In spite of that, the hydropower generation profile is variable over longer time scales, depending on precipitation and water run-off.

The mentioned challenges are addressed to solve by well-tuned control systems and modeling of the generation processes. Since hydropower systems are principally similar (in the meaning of extensive applying of standard components), they match well object- oriented modeling capabilities.

A model of a hydropower system covers the most important parts of the hydropower plant or, for instance, those components which are of interest. The model consists of a mathematical description in the form of differential algebraic equations of physical

processes inside the component (friction, expansion, compression, pressure drop, water hammer effect etc.) and shows the impact to the other units of the hydropower plant. Hence, modeling of the dynamic processes is a crucial tool in hydropower sector control and development.

Typically, for modeling, simulation packages and established libraries of the hydropower plant components are applied. Several modern languages allow to compose and compute a model of a hydropower plant. This thesis considers the equation-based language Modelica and its simulation environments OpenModelica and Dymola, due to well-developed libraries, commercial availability and powerful mathematical apparatus (more detailed overview of chosen language will be given in Chapter 4) [8, 9].

The objective of this thesis is to present a model description for various units of the hydropower system, develop and implement two numeric case studies for the waterway with different configuration and simulate the composed models. Consideration of standard frequency and power control methods is of interest as well.

1.2 Previous work

Since the first model of a hydropower system was developed, it has been of interest to formulate the model of physical processes as close to the real system as possible. Furthermore, it is crucial to reach model accurate reflection to the dynamic of the physical system. This can be approached by model reduction considering some assumptions. The most applicable assumptions in hydropower systems modeling are: compressibility of working liquid, elasticity of the piping system and water column, thermal expansion, liquid density change, temperature deviation, loss, non-linearity of model, water hammer and cavitation effect, flow swirl, open channel, dam type etc. Therefore, there is a diversity of research directions within hydropower system modeling.

One of the most fundamental and pioneering investigation within hydraulic turbine and turbine control models was made by IEEE in 1992 [10]. In this work, IEEE Working Committee presented a variety of hydro power plant models and proposed some control techniques of the power generation available in concern to the computing power and technical development at that time [10].

Several of the available investigations on modeling of hydropower system have considered a hydropower system with compressible water column and penstock [12, 11, 13, 14].

In fact, simplified models with assumption about incompressible penstock are still used. These models are aimed to pay more attention to the interaction between electrical and hydraulic system of hydro power plant and disturbances which may occur [13, 14].

A quite comprehensive turbine-penstock model is developed in [15]. In accordance with his research, requirement of the achieving of the desired accuracy level of the turbine-penstock models can be met by consideration of the non-linearity of the system behavior [15]. The nonlinear models of the hydropower system were likewise considered in [16, 17, 14]. The novel inelastic linearized model of the unsteady flow for the tailrace system with an open channel and water hammer effect consideration was developed in [19, 18].

There is also quite developed research field dedicated to run-of-river hydropower plant object-oriented modeling [20].

A considerable number of investigations are connected with control system improvement. Thus, in [21], the optimization of hydropower production deviation is in focus. To analyze the reason for power production deviation, a reference analytical model based on the Francis turbine was developed, and implemented in Modelica using HydroPower Library of Modelon AB in [21]. In [22], different control algorithms are considered, and the appropriate hydropower plant simulator is developed. In [23], the analysis of the primary control system for the case of isolated model of hydropower plant is of interest.

There are several works which has as objective the estimation of wicket gate loads, based on CFD study. Thus, in [24] investigation of hydrodynamic loads on a wicket gate was performed. A hydropower system with Kaplan turbine was taken as case study.

In [25] the research is focused on the transient phenomena impact and optimization of the controllers and governor parameters in accordance with operating conditions the power plants may face to provide an efficient and safety operation control of the system [25, 26]. The prediction of transient modes consequences are based on numerical simulation of the dynamic behavior of the entire system implemented in SIMSEN software developed by the Laboratory of Electrical Machines of the EPFL [25, 27].

In [28], the effect of penstock parameter variation on mechanical power is of interest. In order to analyze the system response, the authors developed the nonlinear model of a turbine and long penstock without hydraulic friction losses [28]. As implementation environment for the developed model MATLAB SIMULINK was used.

1.3 Overview of thesis

The main distinctive features of this thesis are:

1. Based on a developed model of the hydropower plant, the following six case studies were simulated in OpenModelica:

   a) without surge tank (Francis and Pelton turbines)

   b) with upstream surge tank (Francis and Pelton turbines)

    c) with upstream and downstream surge tanks (Francis and Pelton turbines)

2. The developed model for Francis turbine was validated by means of comparison analysis of simulation results both with hill charts and look-up table based on the turbine geometry.

Specifically, in Chapter 2 a general overview of main hydropower system components are given. Based on this overview, conclusion about the elements to be included in the future model of the hydropower system was made.

Chapter 3 presents a mechanistic model of the hydropower system in the form of differential algebraic equations for the chosen system components and case studies in Chapter 2.

Chapter 4 gives an brief overview of Modelica language and Dymola simulation environmental. The main advantage and mathematical apparatus capabilities are specified. In the second sub-chapter the simulation results of case studies are presented. Also, the comparison analysis of the obtained results vs. hill charts and look-up table is given.

Chapter 5 includes the brief information about relevant to the considered hydropower system types of control. The appropriate variant of the control system is presented.

Chapter 6 introduces the conclusions and discussion of the perspectives for future research.

2 System overview

This chapter gives overview of the basic components of a hydropower system. Hydropower systems are very divers in terms of plant type and size, generating unit type and size, the height head, their sizes and purposes (i.e. electricity generation, capacity or multipurpose) [3].The common primarily classification of the hydropower plants includes three functional classes:

1. Run-of-river hydropower plants harness energy for electricity production mainly from the available flow of the river [3]. Thus, the generation profile is predominantly driven by natural river flow conditions or releases from any upstream reservoir. In such a system, instead of a reservoir, part of a natural river flow diverts into the turbine waterway. Hence, there is no such upstream reservoir and generation depends on precipitation and runoff. In this case generation profile has substantial daily, monthly, seasonal and yearly variations. A short-term storage ("pondage") is to be included to run-of-river hydropower system to provide hourly and daily flexibility in load demand profile adapting.

2. Reservoir (or storage) serves for water storing to provide the flexibility of electricity generation on demand, and diminish dependency on the inflow variability [3]. Reservoirs are classified by their size, electrical capacity and generation potential. Due to design features of the reservoir hydropower systems, they can be used to cover both base (it means that generation takes place round-the-clock and in all seasons) and peak loads (conversely, the generation takes place during hours of peak demand).

3. Diversion system implies separation of a part of the river from a main stream and diverted to a tunnel/canal. Then it proceeds to the hydropower system and afterwards joins the main stream of the river again [21].

4. Pumped storage plants serve as on-grid electricity storage. From a downstream reservoir water is pumped into a upstream reservoir when exceeding of electricity supply takes place. When demand exceeds instantaneous electricity generation, the electricity generates by releasing of stored water and flowing back from the upstream to the downstream reservoir through the turbine. So, principally, both the pumped storage and reservoir hydropower systems serve to store potential energy in the form of elevated water for generating on demand [3]. The distinction is that the pumped storage systems consume energy from the grid to lift the water up, and return most of this energy to the grid later. Thus, the effective (efficiency approach

from 70% to 85%) electricity storage is provided. Nowadays, 99% of on-grid storage is represented by pumped storage systems.

The following work considers only the reservoir hydropower systems. The principal scheme of the typical reservoir hydropower system is shown in figure 2.1.
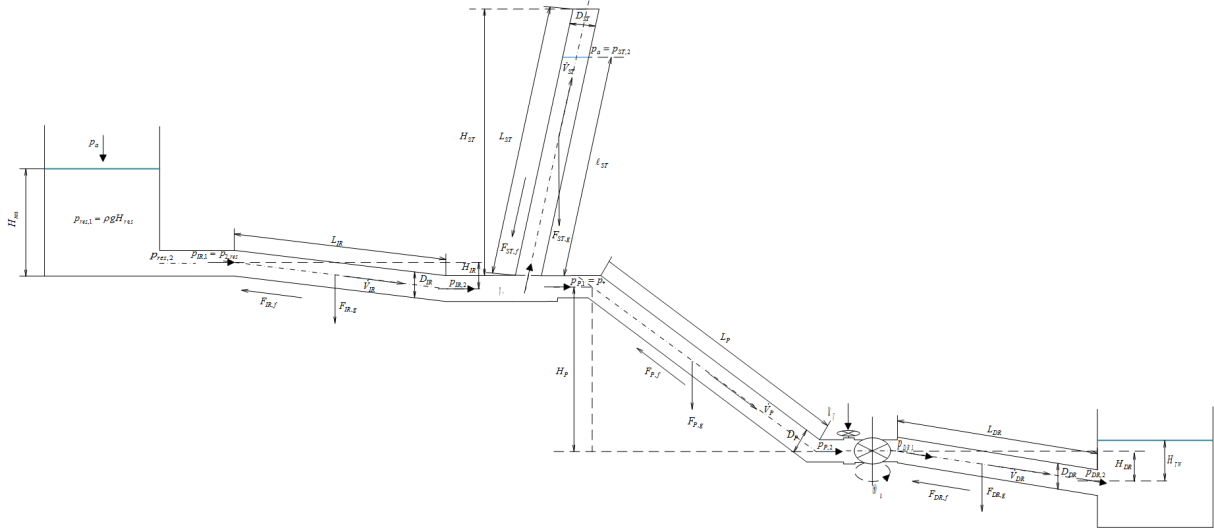
Figure 2.1: Principal scheme of a hydropower system [29]

According to approved standards of the hydropower plant constructions discussed in [30], starting at the reservoir, the following elements are installed: a coarse trash rack, intake gate, intake race tunnel, surge tank (if needed, a surge shaft can be installed in addition), sand trap, fine trash rack, penstock isolating valve with air valve, penstock, spherical valve, turbine, draft tube, draft tube gate, outlet surge shaft and tale race tunnel. Since all components of the hydropower system are connected in series, the valves and gates are important elements of hydropower system for controll and regulation pruposes, to meet safety requirements in case of failure and to provide possibility for technical maintenance. Technical characteristics of these valves have to meet the following operational requirements: flood control, water tightness, set minimum hoist capacity, convenience of installation and maintenance, failure free performance and avoidance of safety hazards to the operating staff and the public [31].

Water from the reservoir passing through the coarse trash rack enters the intake race tunnel via the intake gate and proceeds to the manifold and further to the penstock before reaching the turbine gate. Next, it goes ahead into the scroll casing causing rotation in the turbine. The turbine rotor is connected with the generator rotor by the shaft coupling element. The entering water flow is regulated by wicket gate, which in its turn is actuated by a servomotor controlled by the governor [30]. The driving force for the governor is the deviation between the developed torque and the electricity demand. The gross head of

the water in the hydropower system is determined by the difference between elevation of upstream and tail reservoir. In real systems, the gross head is less than the mentioned elevation difference, because of energy loss due to friction [21].

Hence, the hydropower system can be divided into the following structural blocks: reservoir, conduit system (waterway), hydropower turbine, generator and system outlet. The following sections give operation principles for main components of the hydropower system.

2.1 Reservoir

The reservoir is aimed to store water which is the working body in the hydropower plant system. The reservoir can be formed on the basis of a lake or a river. The water height level in the reservoir is one of the key factors which determine the hydraulic effect of the hydropower plant. To store enough amount of the working body based on the natural reservoir (lake, river) for the needed hydraulic effect, the dam should be constructed. Thus, the steadiness of the production irrespective of varying precipitation or inflow to the reservoir is provided. There are different types of dams. In [32] the following categorization of dams is proposed:

1. Embankment dam (including huge diversity of dam types depending on utilization of available materials (mostly natural materials like soil, gravel, stone, moraine); the initial classification is presented by earthfill and rockfill embankments [32])

2. Concrete dam (covering major types of concrete dams as gravity, buttress and arch dams and variety of more or less common variants of the mentioned above major types)

2.2 Conduit system/waterway

The conduit system is a piping system which convey water from the water intake to the turbine. The waterway includes water intake, intake race (constructed as open channel or tunnel), sand trap, trash racks, manifold, penstock, air vessel, surge tank and surge shaft [30, 29]. If the intake race is constructed as open channel, the system can be dug in the ground, blasted in rock or built up of wood or concrete in the form of an inclined channel (chute).

2.2.1 Water intake

The water intake is following by the reservoir. Since the reservoir is open, trees, branches, stones, debris and other bulky trash may enter and cause hazardous damage or failures of the system. Hence, their entering into the hydro power plant system must be prevented.

For preventive purpose, the water intake zone should be equipped with a coarse trash rack [30]. Some hydropower systems have a deep water intake which allows to skip trash rack and has better regulation capabilities. In this case, below the water intake, a sump is to be constructed.

For technical maintenance or emergency situations when conduit system emptying is required, an intake gate is to be installed to shut off water delivery. Since leakage through the main gate can occur, a small gate may be arranged for drainage purposes.

2.2.2 Intake race

The part of the waterway between water intake and the surge tank is denoted the intake race. The intake race may be drilled, blasted or bored in the rock. The boring method allows to obtain smoother surface inside the intake race and, consequently, reduce the friction head loss for the same cross section consequently [30]. The intake race ends with a sand trap.

2.2.3 Sand trap

The sand trap is a part of the intake race with gradually increasing cross-section. This component is used to improve sedimentation of suspended particles [31, 30]. The widened cross-section of the tunnel in the zone following the sump causes significant reduction of the water velocity. Thus, sand sediment is collected and transported away from this zone through the transport tunnel via connecting gates [31]. The shape of the sand trap is a rectangular basin. The sand trap helps to reduce the erosion processes on the mechanical components of the valves and turbine [31]. In order to prevent bypassing of sand, the sand trap basin should be emptied at fixed time intervals set in accordance with the hydropower plant operation and maintenance schedule.

2.2.4 Fine trash rack

A fine trash rack is usually installed before the penstock. The fine trach rack is a valuable element of the system which is aimed to prevent entering of debris of smaller stones downstream the system. Thus, a fine trash rack is a double-protection system of the

valve and the turbine together with sand trap for the case when the last one is full or omitted [30]. The difference between coarse and fine trash racks is in the bar size: the spacing of bars in a fine trash rack is smaller than in the coarse rack [31]. Here, the dimensions should be chosen in consideration to withstand a completely clogged trash rack [31]. To prevent resonance problems and fatigue fractures of the bars, the frequency of the bars must not be equal to the Von Karmans vortex frequency [31]. For analysis of oscillating flow mechanism, the dimensionless Stouhals number must be in a range of 0,19-0,20[31].

2.2.5 Surge tank

While water flow is proceeding trough the waterway it can accelerate or decelerate causing pressure variations with magnitude exceeding the nominal pressure in the waterway, which, in its turn, leads to the load changes causing the mass oscillations [30, 21]. This large pressure oscillations is called "water hammer" effect. The intensity of the water hammer effect is defined by the length of the waterway and the magnitude of acceleration or deceleration. Thus, the piping system of the waterway should be reinforced sufficiently (which usually is not economically feasible) or the magnitude of possible pressure variations should be controlled in an appropriate way. There are several water hammer prevention means that can be applied: limitating the gate or valve closing time, pressure regulator valves installed close to the turbine, surge tank and surge shaft [21]. In this thesis a surge tank is considered as a water hammer prevention mean. The surge tank connects to the intake race and the penstock by manifold [29]. The size of the surge tank should be large enough to fulfill the requirement of a stability criteria (Thoma criteria) and be able to reduce the maximum magnitude of pressure variation in the tunnel to an appropriate level [31].

2.2.6 Surge shaft

Surge shaft is a surge tank with small cross section area. The surge shaft is installed additionally to the surge tank.

2.2.7 Penstock

The penstock is a pipe either welded of steel plates, or made of concrete or wood, This pipe serves to connect the pressure tank and turbine inlet valve in the machine hall [30]. The penstock can be lined and unlined. A choice of the appropriate shaft depends on the rock quality. If the rock quality is sufficiently high, an unlined pressure shaft is more economical and technically suitable. Otherwise the shaft is being lined by concrete or steel

plate mining embedded in concrete [30]. The penstock lining increases the cost, however, it contributes to losses reducing.

There are also possibilities for inside and outside installation of penstock in the rock. In case of installation inside the rock, the penstock is embedded in a concrete plug. For installation above ground, the penstock should be mounted on foundation concrete block and fixed in reinforced concrete anchoring blocks in definite points.

The length of the penstock is an important parameter proportional to the water inertia and influences on the dynamic height loss [33]. An automatic isolating/shut-off valve at the upstream end of a penstock must be installed. This valve provides automatically closing if a pipe rupture takes place.

2.2.8 Penstock isolating valve

The penstock isolating valve is a butterfly type valve, which closes if the water velocity is higher than 1,25 of the water velocity at full power output of the plant [31]. The necessity of the isolating valve installation depends on the length of the intake race.

2.2.9 Air vessel

In order to mitigate pressure fluctuation caused by pumps, vortex shedding, valves closing/opening, etc. in a hydropower system with closed surge tank, an air vessel is used [25].

2.3 Hydropower turbine

2.3.1 Turbine inlet valve

A turbine inlet valve should be installed prior to the turbine. The type of valve is defined by the turbine type. Thus, for high pressure turbines, a spherical valve is recommended [31]. To prevent cavitation damage of the valve seal, the turbine inlet valve must be drop tight [31].

2.3.2 Turbines

The Pelton turbines are used for high heads and small flows. In the Pelton turbines water passes through nozzles and strikes spoon-shaped buckets arranged on the periphery of a wheel.

Francis turbines accommodate a wide range of heads (20 m to 700 m), small to very large flows, a broad rate capacity and excellent hydraulic efficiency [3]. Therefore, Francis turbines are the most common and widely-used turbine type. Guide vanes direct the water tangentially to the turbine wheel.Then, the water enters the wheel and exits it in the middle [3]. For output optimization and efficiency over the variations in head and flow conditions, the guide vanes are adjustable.

For Kaplan turbines the operating range is low heads and large flows. The Kaplan turbine is a propeller-type turbine with adjustable blades [3].

2.3.3 Cavitation and sand erosion

Water turbines are often affected by impact of cavitation and sand erosion. High head turbines (above 250 m) are primarily in the risky zone due to high pressures, pressure variations and high water velocities [30].

Cavitation in the waterway/turbine occurs due to vaporization of water at low pressure condition and re-condensation to liquid water. This creates some phase pulsation leading to local high pressure spikes in pressure which may easily destroy equipment such as turbine blades [29]. The main condition for vaporization is a decrease in the local pressure below the saturation pressure of water at the given temperature [29].

For a Francis or Kaplan turbine, the runner and draft tube cones are exposed to cavitation, while for a Pelton turbine the needle, nozzles and the runner buckets are attacked mostly by cavitation. This has stimulated a progressive development of a material science applied to hydropower turbines. Today, guide vanes and runners exposed to high flow velocities with high risk of cavitation and turbulence corrosion are preferably made of stainless steel 13% Cr 4% Ni and 16% Cr 5% Ni respectively [30]. The 16% Cr 5% Ni stainless steel is also used for the upper part of the draft tube cone, surface of the covers against the guide vane end faces. The hardened stainless steel of 13% Cr 4% Ni or 16% Cr 5% Ni is used for the parts exposed to high flow velocities such as needle tips and nozzles.

Sand erosion occurs mainly on the plants at net heads above 200 - 300 m. Sand erosion implies some abrasive wear, which is able to destroy the oxide layer on the flow guiding surfaces and can lead to unevenness of the surfaces which may be the origin also for cavitation erosion [30]. There are some differences between the effects sand erosion can make for Pelton and Francis turbines. Thus, in the case of Pelton turbines, the needle

tip, the seal rings in the nozzles and the runner buckets are affected by sand erosion. Here, the particle size is an important parameter which defines the localization and type of the damages. This phenomenon is caused by the turbulence occurrence in the high jet velocity bringing the grain particles to oscillate and rotate in circles leading to collisions with the steel surface [30]. For a Francis turbine, the guide vane cascade and the labyrinth rings are mostly exposed to the sand erosion.

2.3.4 Closing valve

A closing valve must be installed upstream the turbine. There are various types of closing valves, such as a gate, butterfly valve, gate valve, spherical valve etc [30].

2.4 Generator

The generator is used in the hydropower systems in order to perform the conversion of mechanical energy from the turbine into electric energy. This conversion process is described by Faraday's law:

$$\varepsilon = -N\frac{d\Phi_B}{dt} \tag{2.1}$$

Principally, the generator consists of a rotating part (the rotor) and a stationary part (the stator). According to Faraday's law, the rotating magnetic field delivered by the rotor, induces voltage in the copper coils in the stator.

Generators can be divided into synchronous and asynchronous generators. The first type is widely applied in bigger hydro power plants, while, on smaller hydropower plants (less than 5 MW) asynchronous generators are more applicable [21].

2.5 System outlet

2.5.1 Draft tube

The waterway ends with a draft tube. In [31], it is referred to the downstream part of the turbine. The draft tube serves to convey the water from the turbine to the downstream reservoir (tail water). Due to specific configuration with a gradually increasing cross-section towards the downstream reservoir, the remaining kinetic energy at the runner outlet is converted to pressure energy at the draft tube outlet [31].

2.5.2 Draft tube gate

The draft tube gate has an isolating function, to provide access to the draft tube and turbine for inspection or maintenance. At the normal operation regime of the turbine, the draft tube gate is locked and secured [31].

2.5.3 Outlet surge shaft

The outlet surge shaft is aimed to reduce a low pressure wave in order to separate the water column beneath the turbine runner when shut down of the turbine is occur. The size of the outlet surge shaft should be chosen in a way to fulfil the requirement of the maximum surge level to flood the power house during shut down of the turbines which following by the start simultaneous with the adverse point of surge time of the outlet tunnel system. Otherwise the restriction on the turbine's start sequence after shut down must be set [31].

2.5.4 Outlet tunnel

This component is the last one before the downstream reservoir. The design of the outlet tunnel is similar to the intake race tunnel.

3 Model development

The following chapter develops mechanistic model for each system component. For this model, assume that the hydropower system consists of the following components: reservoir, intake race, manifold, upstream surge tank, penstock, turbine, generator, governor, discharge race, downstream surge tank, and tail water reservoir. These components are assumed to include to the model, based on the component's contribution to a dynamics of the entire hydropower system.

3.1 Reservoir

In the following model, the reservoir is assumed as an open pound (Figure 3.1).
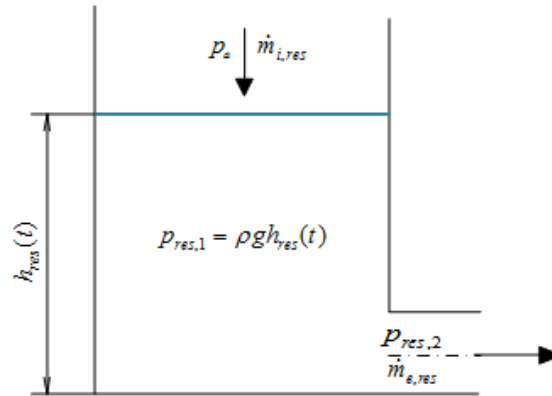
Figure 3.1: Schematic representation of the model for flow through reservoir with water level as a time function. [29]

From a pressure balance of a reservoir, the pressure at the water intake (the outlet of the reservoir) is the sum of atmospheric pressure and static pressure of the dam depending on the water height in the dam. So that:

$$p_{\mathrm{a}} + p_{\mathrm{res},1} = p_{\mathrm{res},2} \tag{3.1}$$

$$p_{\mathrm{res},1} = p_{\mathrm{st,res}} = \rho g h_{\mathrm{res}}(t) \tag{3.2}$$

The mass balance of the dam:

$$\frac{dm_{\text{res}}}{dt} = \dot{m}_{\text{i,res}} - \dot{m}_{\text{e,res}} \tag{3.3}$$

For model simplification, the water level in the reservoir is assumed as constant or with insignificant variation which impact is not essential to the model of entire hydropower system (Figure 3.2).

This assumption can be considered due to inertia of the reservoir as a system, since the time period for water level changing in the reservoir can be considered as very large to the time period for pressure and mass flow changing inside the hydropower system. Therefore,
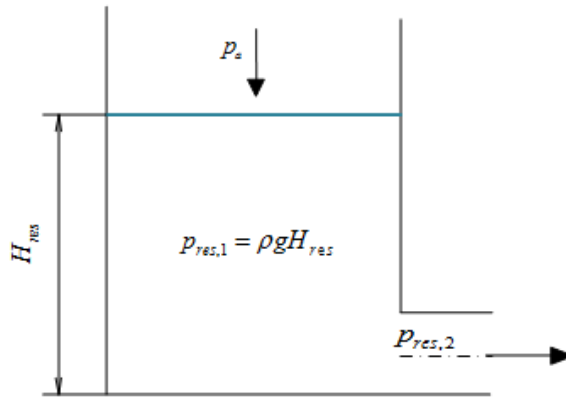
Figure 3.2: Schematic representation of the model for dam with constant water level

the reservoir model can be reduced to:

$$p_a + p_{\text{res},1} = p_{\text{res},2} \tag{3.4}$$

$$p_{\text{res},1} = p_{\text{st,res}} = \rho g H_{\text{res}}$$

$$p_{\text{res},2} = p_{\text{IR},1}$$

3.2 Inlet race

Schematically the model of the intake race is shown in figure 3.3. Momentum balance:

$$\frac{d\mathcal{M}_{\text{IR}}}{dt} = \dot{\mathcal{M}}_{\text{IR,i}} - \dot{\mathcal{M}}_{\text{IR,e}} + F_{\text{IR},\Sigma} \tag{3.5}$$

Assume: $\dot{\mathcal{M}}_{\text{IR,i}} = \dot{\mathcal{M}}_{\text{IR,e}}$, so that equation 3.5 can be reduced to:

$$\frac{d\mathcal{M}_{\text{IR}}}{dt} = F_{\text{IR}} \tag{3.6}$$
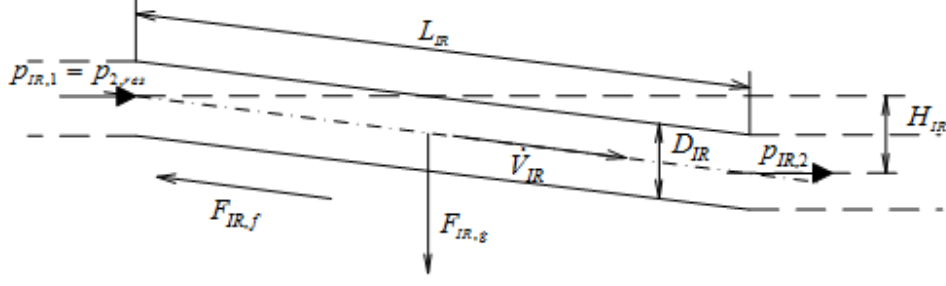
Figure 3.3: Schematic representation of the model for inlet race

$$\mathcal{M}_{IR} = \frac{m_{IR}}{A_{IR}}\dot{V}_{IR}, \ m = \rho V_{IR}, \ V_{IR} = \pi r_{IR}^2 L_{IR} = \pi \left(\frac{D_{IR}^2}{4}\right) L_{IR}$$

The forces acting in the inlet race:

$$F_{IR} = F_{IR,p} + F_{IR,g} - F_{IR,f} \tag{3.7}$$

$$F_{IR,p} = p_{IR,1}A_{IR} - p_{IR,2}A_{IR}, \ F_{IR,g} = m_{IR}g\frac{H_{IR}}{L_{IR}}, \ F_{IR,f} = \frac{K'''_{IR}A_{IR,w}f_{IR,D}}{4}$$

$$A_{IR,w} = \pi D_{IR}L_{IR}, \ K'''_{IR} = \frac{\rho}{2A_{IR}^2}\dot{V}_{IR}\left|\dot{V}_{IR}\right|$$

$$\frac{1}{\sqrt{f_{IR,D}}} = -2\lg\left(\frac{\varepsilon_{IR}}{3,70D_{IR}} + \frac{5,74}{N_{IR,Re}^{0,9}}\right) \tag{3.8}$$

$$N_{Re,IR} = \frac{\rho \dot{V}_{IR}D_{IR}}{\mu A_{IR}}$$

3.3 Manifold

The main purpose of the manifold is to connect the outlet of the inlet race, the inlet of the penstock and the inlet of the upstream surge tank. By assuming that there is negligible mass (inertia) inside the manifold, steady state for both mass and momentum balances can be assumed [29]. Since no mass is accumulated, the mass balance of the manifold can be represented as:

$$\frac{dm}{dt} = 0$$

$$\dot{V}_i = \dot{V}_P + \dot{V}_{ST} \tag{3.9}$$

The momentum balance of the manifold:

$$\frac{dM}{dt} = 0$$

$$p_{IR,2} = p_{P,2} = p_{ST,1} = p_*$$

3.4 Penstock

Principally, a penstock is a steep pipe (Figure 3.4) which connects the inlet part of the hydropower system (via the manifold) and the wicket gate inlet to the turbine.
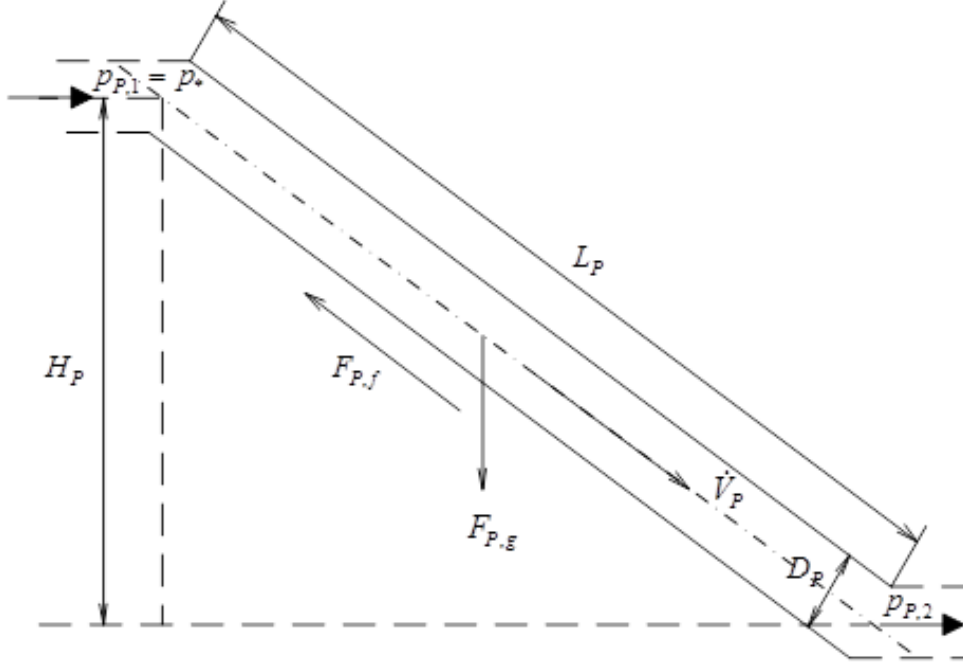
Figure 3.4: Schematic representation of the model for flow through the penstock

By assuming no leakage through the penstock piping system, the influent mass flow is equal to the effluent one, so that:

$$\frac{dm_P}{dt} = \dot{m}_{i,P} - \dot{m}_{e,P} = 0 \tag{3.10}$$

$$\frac{dM_P}{dt} = F_P \tag{3.11}$$

$$M_P = \frac{m_P}{A_P}\dot{V}_P, \; m_P = \rho V_P, \; V_P = \pi r_P^2 L_P = \pi \left(\frac{D_P^2}{4}\right) L_P$$

The forces acting in the penstock:

$$F_P = F_{P,p} + F_{P,g} - F_{P,f} \tag{3.12}$$

$$F_{P,p} = p_{P,1}A_P - p_{P,2}A_P, \; F_{P,g} = m_P g \frac{H_P}{L_P}, \; F_{P,f} = \frac{K''' {}_P A_{P,w} f_{P,D}}{4}$$

$$A_{\mathrm{P,w}} = \pi D_{\mathrm{P}} L_{\mathrm{P}}, \ K_{\mathrm{P}}''' = \frac{\rho}{2A_{\mathrm{P}}^2} \dot{V}_{\mathrm{P}} \left| \dot{V}_{\mathrm{P}} \right|$$

$$\frac{1}{\sqrt{f_{\mathrm{P,D}}}} = -2 \lg \left(\frac{\varepsilon_{\mathrm{P}}}{3,70 D_{\mathrm{P}}} + \frac{5,74}{N_{\mathrm{Re,P}}^{0,9}} \right) \tag{3.13}$$

$$N_{\mathrm{Re,P}} = \frac{\rho \dot{V}_{\mathrm{P}} D_{\mathrm{P}}}{\mu A_{\mathrm{P}}} \tag{3.14}$$

3.5 Surge tank
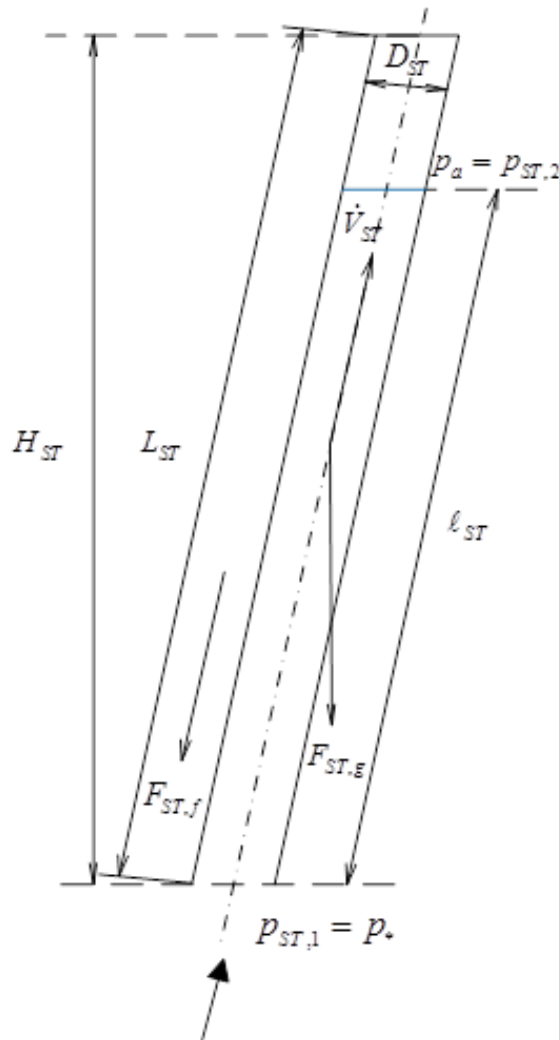
Figure 3.5: Schematic representation of the model for flow through the surge tank

The pressure balance of the surge tank can be represented as:

$$p_{ST,1} - \Delta p_{ST} = p_{ST,2} \tag{3.15}$$

$$p_{ST,1} = p_*, \ p_{ST,2} = p_a$$

The mass balance:

$$\frac{dm_{hrmST}}{dt} = \dot{m}_{ST,i} \tag{3.16}$$

$$\dot{m}_{ST,i} = \rho \dot{V}_{ST}$$

The momentum balance:

$$\frac{dM_{ST}}{dt} = \dot{M}_{ST,i} + F_{ST} \tag{3.17}$$

$$M_{ST} = \frac{m_{ST}}{A_{ST}} \dot{V}_{ST}, \ m_{ST} = \rho V_{ST}, \ V_{ST} = \pi r_{ST}^2 \ell_{ST} = \pi \left(\frac{D_{ST}^2}{4} \right) \ell_{ST}$$

$$\dot{M}_{ST,i} = \dot{m}_{ST,i} \upsilon = \rho \dot{V}_{ST} \upsilon = \rho \dot{V}_{ST} \frac{\dot{V}_{ST}}{A_{ST}} = \frac{\rho}{A_{ST}} \dot{V}_{ST}^2$$

The forces acting in the surge tank:

$$F_{ST} = F_{ST,p} - F_{ST,g} - F_{P,f} \tag{3.18}$$

$$F_{ST,p} = p_{ST,1} A_{ST} - p_{ST,2} A_{ST}, \ F_{ST,g} = m_{ST} g \frac{H_{ST}}{L_{ST}}, \ F_{ST,f} = \frac{K'''_{ST} A_{ST,w} f_{ST,D}}{4}$$

$$A_{ST,w} = \pi D_{ST} \ell_{ST}, \ K'''_{ST} = \frac{\rho}{2 A_{ST}^2} \dot{V}_{ST} \left| \dot{V}_{ST} \right|$$

$$\frac{1}{\sqrt{f_{ST,D}}} = -2 \lg \left(\frac{\varepsilon_{ST}}{3,70 D_{ST}} + \frac{5,74}{N_{ST,Re}^{0,9}} \right) \tag{3.19}$$

$$N_{Re,ST} = \frac{\rho \dot{V}_{ST} D_{ST}}{\mu A_{ST}} \tag{3.20}$$

Sometimes, the surge tank has a specific form when a cross section is a function of the elevation [25]. In this case, the volume of the surge tank can be found by integration of the cross section which is function of the elevation.

3.6 Stability criterion

For a surge tank design (iterative procedure), the basic parameter is the stability criterion. In hydropower the most common are Thoma (original or modified 3.22) criterion, and Svee criterion 3.23. The equations of the original Thoma stability criterion and Svee criterion are derived in [34].

$$A_{ST} \geq \frac{A_I R L_I R}{2gaH_{eff}} \tag{3.21}$$

$$A_{ST} \geq 1{,}5 \frac{A_I R L_I R}{2gaH_{eff}} \tag{3.22}$$

$$A_{ST} \geq \frac{A_T L_T}{2g \left(a + \frac{1}{2g} \right) \left(H_0 - z_0 + \frac{v_o{}^2}{2g} \right) \left(1 + \frac{Q_0 \Delta \eta}{\eta_0 \Delta Q} \right) + 2\frac{v_0{}^2}{2g}} \tag{3.23}$$

According to Svee criterion, the gross head must be larger than product of head loss and the losses in the turbine. Svee criterion takes into consideration the surge tank location. In the equation 3.23 is assumed an upstream surge tank location. In case of downstream location of the surge tank, when the velocity head will decrease the stability, rather than contribute to it [34], the equation 3.23 can be written as:

$$A_{ST} \geq \frac{A_T L_T}{2g \left(a + \frac{1}{2g} \right) \left(H_0 - z_0 - \frac{v_o{}^2}{2g} \right) \left(1 + \frac{Q_0 \Delta \eta}{\eta_0 \Delta Q} \right) - 2\frac{v_0{}^2}{2g}} \tag{3.24}$$

In [35], it was noted that the equation 3.23 doesn't consider other effects, which impact the stability (for instance, throttling the surge tank, or throttling the tunnel itself).

3.7 Turbine

According to Bernoulli-inspired expression, the pressure drop across the guide vane and the turbine rotor can be Δp_{tr} can be given as following [29]

$$\dot{V}_p = C_V f(u_V) \sqrt{\frac{\Delta p_{tr}}{p_a}} \tag{3.25}$$

For Francis turbine, the guide vane signal depends on the guide vane angle:

$$\alpha_1 = g(u_V)$$

By assuming a linearity of the function $f(u_V) = u_V$, the equation 3.25 can be simplified to[29]:

$$\dot{V}_p = C_V u_V \sqrt{\frac{\Delta p_{tr}}{p_a}}$$

$$\Delta p_{tr} = p_{p,2} - p_{tr,2}$$

Assume a steady energy balance across the guide vane. So that:

$$\dot{K}_p + \dot{P}_{p,2} + p_{p,2}\dot{V}_p = \dot{K}_{tr,2} + \dot{P}_{tr,2} + p_{tr,2}\dot{V}_p - \dot{W}_{ts} - \dot{W}_{f,t} \tag{3.26}$$

Assume the following [29]:

1. The vertical difference between the exit of the penstock and the entrance to the turbine rotor can be neglected, so that: $\dot{P}_{p,2} = \dot{P}_{tr,1}$

2. The diameter of the exit pipe from the turbine is equal to the diameter of the entrance pipe, so that: $\dot{K}_p = \dot{K}_{tr,2}$

3. $\dot{W}_{f,t} \propto \dot{W}_{ts}$, so that it can be assumed that: $(\dot{W}_{f,t} + \dot{W}_{ts})\eta_h = \dot{W}_{ts}$

Considering given above assumption, the equation 3.26 can be reduced to:

$$p_{p,2}\dot{V}_p = p_{tr,2}\dot{V}_p - \frac{\dot{W}_{ts}}{\eta_h}$$

$$\dot{W}_{ts} = \eta_h \left(p_{tr,2}\dot{V}_p - p_{p,2}\dot{V}_p \right) = \eta_h \Delta p_{tr}$$

The increasing diameter of the draft tube after the turbine and a steady energy balance leads to:

$$\dot{K}_{d,1} + \dot{P}_{d,1} + p_{d,2}\dot{V}_d = \dot{K}_{tr,2} + \dot{P}_{tr,2} + p_{tr,2}\dot{V}_p \tag{3.27}$$

Assume the following [29]:

1. The vertical difference between the exit of the penstock and the entrance to the turbine rotor can be neglected, so that:$\dot{P}_{tr,2} = \dot{P}_{d,1}$

2. The diameter of the exit pipe from the turbine is equal to the diameter of the entrance pipe, so that: $\dot{K}_{tr,1} \approx \dot{K}_{tr,2}$

Friction loss in the aggregate rotation

Friction loss in the bearings $\propto \omega_a^2$

Friction loss in gears $\propto \omega_a^2$

Friction loss in air gaps $\propto \omega_a^3$
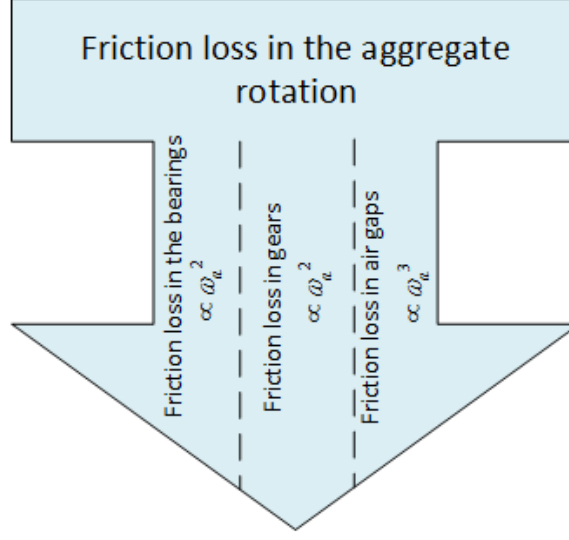
Figure 3.6: The main components of friction loss in the aggregate rotation

So that, the equation 3.27 can bre rewritten as:

$$p_{d,1}\dot{V}_d \approx p_{tr,2}\dot{V}_p + \dot{K}_{tr,1} - \dot{K}_{d,1}$$

$$\dot{K}_{d,1} = \frac{\rho}{2A_d^2}V_p^{\,3}$$

In the ideal case, the $\dot{K}_{d,1}$ has a small value.

The aggregate rotation can be represented via either angular momentum balance, or kinetic energy balance [29]. Considering kinetic energy balance, we get:

$$\frac{dK_a}{dt} = \dot{W}_{ts} - \dot{W}_{f,a} - \dot{W}_g$$

$$K_a = \frac{1}{2}J_a\omega_a^{\,2}$$

A friction loss in the aggregate rotation is multi-component (Figure 3.6).

Assume the prevalence of the bearing friction components in the total friction loses in the aggregate rotation.

$$\dot{W}_{f,a} = k_{f,b}\omega_a^{\,2}$$
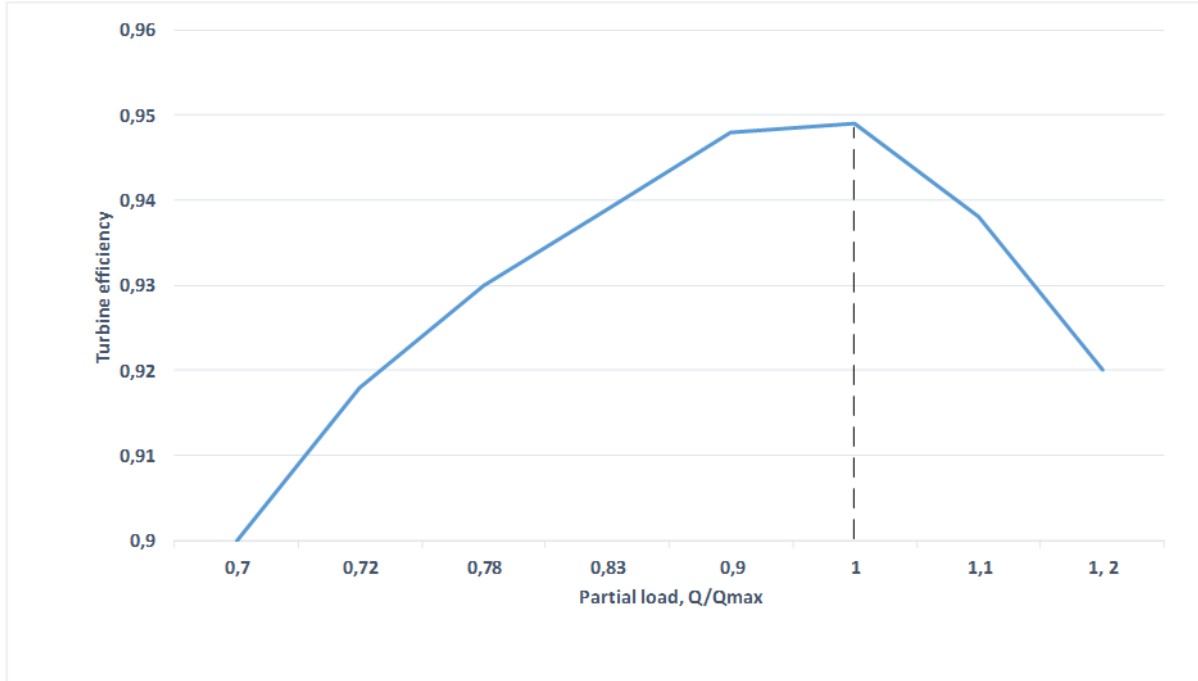
Figure 3.7: Turbine efficiency curve of a Francis turbine vs. partial load

By assuming the efficiency of the generator as η_e, the available electric energy can be given as:

$$\dot{W}_e = \eta_e \dot{W}_g$$

The stability of the hydrpower system depends also on the turbine efficiency [34]. Thus, when the turbine runs at a discharge under the best efficiency point, a load increasing will cause insignificant changes in discharge. In its turn, this will lead to efficiency increasing and manoeuvrability of the turbine for variable power demand. In this case the system is more stable and, thus, less surge tank area is needed[34]. In case of turbine running at the best efficiency point already, the increasing in discharge will cause to the efficiency reduction. In its turn, this will lead to another insignificant discharge increasing, and the system will therefore need a surge tank of larger area. Thus, this case is less stable than a system operating on a load lower than the best efficiency point.

Figure 3.7 shows an efficiency curve of a typical Francis turbine, with varying for different partial loads.

For a Pelton or Kaplan turbines, the curve will have another form.

3.8 Generator

The angle between generator torque and the grid frequency, can be described by the angle between the generator stator and rotor in a rotating reference frame between generator torque and the grid frequency [36]. The angle is related to the angular grid frequency:

$$\omega_{\text{grid}} = 2\pi f_{\text{grid}} \tag{3.28}$$

In a case of synchronous generators connection to the grid, the synchronous angular speed of rotation can be defined by the grid frequency:

$$\omega_{\text{s}} = \frac{2}{P}\omega_{\text{grid}} \tag{3.29}$$

The angular speed of rotation of the turbine, ω_{tr}, has to be equal to the synchronous speed for the steady state operation mode. When the load change occurs, the change in angle between the generator stator and rotor can be found as [36]:

$$\frac{d\delta}{dt} = \frac{2}{P}\omega_{\text{tr}} - \omega_{\text{grid}} \tag{3.30}$$

Concerning to equation 3.30, the angle increases in case of increasing of the electrical load leading to the grid frequency decreasing and, thus, a positive change of δ. Otherwise, the angle will decrease.

Assume:$\delta \approx \sin\delta$] [36, 37]. So that:

$$T_{\text{g}} = T_{\text{g,R}}\frac{\sin\delta}{\sin\delta_{\text{R}}} \tag{3.31}$$

Where the subscript R is related to the related values.

By means of the torque equation, the damping of the angular movement can be described:

$$I_{\text{p}}\frac{d\omega}{dt} = \rho\dot{V}\left(t_{\text{s}} - r_2^2\omega\right) - T_{\text{g}} - m_{\text{d}}\frac{d\delta}{dt} \tag{3.32}$$

Where m_d is the angular movement damping coefficient.

3.9 Governor

The governor frequency is introduced by means of following system of differential equations [36, 37]:

$$\begin{cases} \frac{dy}{dt} = c \\ \frac{dc}{dt} = \frac{y_{\text{ref}}}{T_{\text{K}}}\left[-\frac{1}{b_{\text{t}}n_{\text{ref}}}\frac{dn}{dt} + \frac{1}{b_{\text{t}}T_{\text{i}}}\frac{(n_{\text{ref}}-n)}{n_{\text{ref}}} - \frac{b_{\text{p}}T_{\text{K}}+b_{\text{t}}T_{\text{i}}}{b_{\text{t}}T_{\text{i}}}c - \frac{b_{\text{p}}}{b_{\text{t}}T_{\text{i}}}\left(y_{\text{ref}} - y\right)\right] \end{cases} \tag{3.33}$$

Where y is the servo motor position and c is the servo motor velocity. The equation 3.33 are derived from the transfer function of the PI-governor for case of permanent speed droop and servo motor time constant [36]. In the hydropower system, the volumetric flow rate is defined by the opening degree of the turbine [36]. In [38] was assumed the turbine acts as a valve with a varying opening degree, which is defined by the dimensionless valve equation:

$$\kappa = \frac{\dot{V}}{\dot{V}_R} \frac{\sqrt{2gH_R}}{\sqrt{2gH}} \tag{3.34}$$

Where $\dot{V}_R$ and H_R are the volumetric flow rate and the rated head respectively.

Since the position of the servo motor is a proportional function of the turbine opening degree (Figure 5.1) [36], the differential equations 3.34 can be defined by means of the turbine opening degree instead of servo motor position by direct replacing *kappa* and *y*.
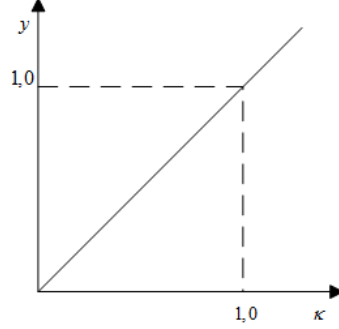
Figure 3.8: The relation between the position of the servo motor and the turbine opening degree

3.10 Discharge race

Schematically the model of the discharge race is shown in figure 3.9. Assume the transitional duct between the turbine and the inlet to the discharge race is of considerably small value, so that it can be neglected. The momentum balance of the discharge race:

$$\frac{dM_{DR}}{dt} = \dot{M}_{DR,i} + F_{DR} \tag{3.35}$$

$$M_{DR} = \frac{m_{DR}}{A_{DR}}\dot{V}_{DR}, \; m_{DR} = \rho V_{DR}, \; V_{DR} = \pi r_{DR}^2 L_{DR} = \pi\left(\frac{D_{DR}^2}{4}\right)L_{DR}$$

The forces acting in the discharge race:

$$F_{DR} = F_{DR,p} + F_{DR,g} - F_{DR,f} \tag{3.36}$$
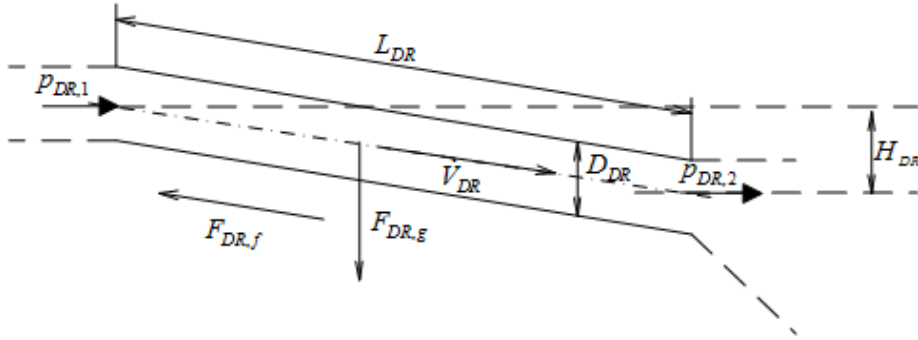
Figure 3.9: Schematic representation of the model for discharge race

$$F_{\text{DR,p}} = p_{\text{DR,1}}A_{\text{DR}} - p_{\text{DR,2}}A_{\text{DR}}, \ p_{\text{DR,2}} = p_{\text{a}} + \rho g H_{\text{TW}}$$

$$F_{\text{DR,g}} = m_{\text{DR}}g\frac{H_{\text{DR}}}{L_{\text{DR}}}, \ F_{\text{DR,f}} = \frac{K'''_{\text{DR}}A_{,w}f_{\text{DR,D}}}{4}$$

$$A_{\text{DR,w}} = \pi D_{\text{DR}}L_{\text{DR}}, \ K'''_{\text{DR}} = \frac{\rho}{2A_{\text{DR}}^2}\dot{V}_{\text{DR}}\left|\dot{V}_{\text{DR}}\right|$$

By assuming that $\dot{V}_{\text{DR}} = \dot{V}_{\text{P}}$

$$\frac{1}{\sqrt{f_{\text{DR,D}}}} = -2\lg\left(\frac{\varepsilon_{\text{DR}}}{3,70D_{\text{DR}}} + \frac{5,74}{N_{\text{DR,Re}}^{0,9}}\right) \tag{3.37}$$

$$N_{\text{Re,DR}} = \frac{\rho\dot{V}_{\text{DR}}D_{\text{RD}}}{\mu A_{\text{RD}}} \tag{3.38}$$

4 Simulation of the study cases

4.1 Modelica overview

Modelica is a modern object-oriented modeling language which has become quite popular in the last ten years due to commercial availability and wide range of modeling and simulation tools.

Modelica was developed by a non-profit organization "The Modelica Association". Its members from Europe, U.S.A., Canada and Asia have been working on the open standard Modelica and the open source Modelica Standard Library development since 1996. Today, Modelica (along with related to it technologies) is a continuously developing modeling language, performed within the ITEA2 projects EUROSYSLIB, MODELISAR, OPEN-PROD, and MODRIO [8].

The mathematical apparatus is represented by differential, algebraic and discrete equations [8]. The capacity of the mathematical apparatus of Modelica allows to implement multi-domain models of large and heterogeneous systems of various complexity. It is widely used for mechatronic models in robotics, automotive and aerospace applications involving mechanical, electrical, hydraulic control and state machine subsystems, process oriented applications and generation and distribution of electric power [8]. Modelica has good developed libraries with a large set of model components and function from many domains. Commercially available and free of charge simulation environments (CATIA, Systems, Dymola, LMS AMESim, JModelica.org, MapleSim, OpenModelica, SCICOS, SimulationX, Wolfram SystemModeler etc.) along with possibility to convenient import into Simulink (using export features of Dymola, MapleSim, and SimulationX) makes Modelica one of the most preferable modern object-oriented modeling language in industry.

While the debugging process in Modelica codes is quite challenging, the issues of the Modelica Language and to the Modelica Standard Library are reported via the Modelica issue tracking system [8]. As it was mentioned above, the energy production using hydropower systems is valuable and wide used technology in Norway. That is why it is of interest to provide proper control system and investigate in details the physical processes inside the hydropower system. The entire waterway from a reservoir to the generation aggregate is relatively easy to formulate in state space form as differential algebraic equations (DAEs), but considerably more complex to formulate in state space form as ordinary differential equations (ODEs) [8]. So that, it is advantageous to encode hydropower system models

in languages supporting DAEs (such as Modelica, for instance) and appropriate solvers and simulation environmental [8].

In the following work, it is of interest to investigate how waterway models can be rigorously formulated as DAEs by means of mass, momentum and mechanical energy balances (mechanistic model) with added algebraic constitutive equations, including models for different types of turbines (Pelton and Francis turbines) [8].

4.2 Simulation of the study cases

To illustrate the models, the following realistic numerical case studies were simulated (for both Francis and Pelton turbines):

- without surge tank (for Francis and Pelton turbines)
- with upstream surge tank (for Francis and Pelton turbines)
- with upstream and downstream surge tanks (for Francis and Pelton turbines)

The developed model can be used for further investigation of dynamics and control of the system.

4.2.1 Hydropower system with Francis turbine

In this subsection, results of the simulation of a hydropower system with Francis turbine are given. For the simulation of the developed mechanistic model, study cases from literature sources were used [31, 36, 39] and is given in Table 4.2.1.

Parameter	Value	Units
H	270	m
Q	20,8	$\frac{m^3}{s}$
N	500	rpm

The hydropower system without surge tank   The simulation results of the developed mechanistic model is illustrated on Figure 4.1

The hydropower system with upstream surge tank   The simulation results of the developed mechanistic model is illustrated on Figure 4.2
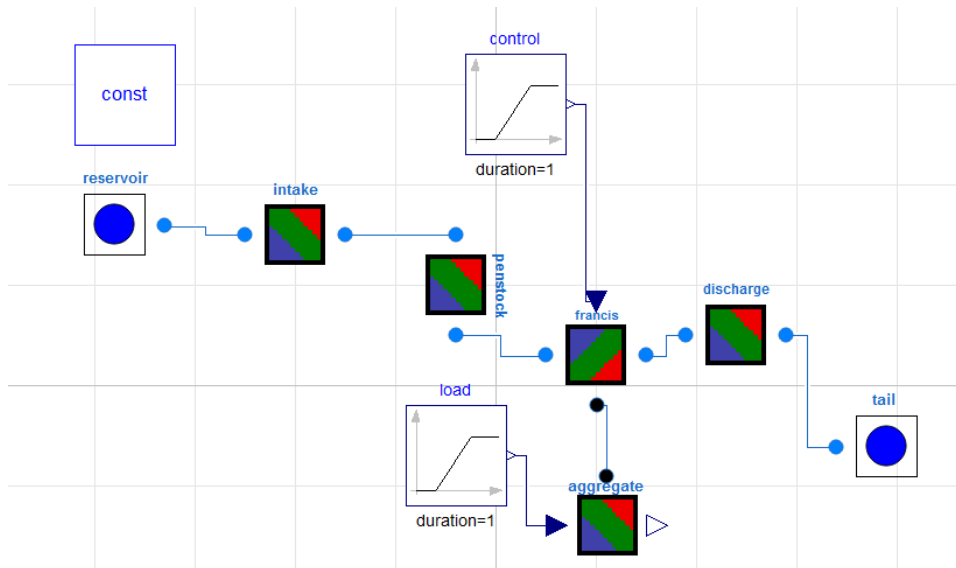
Figure 4.1: The hydropower system without surge tank
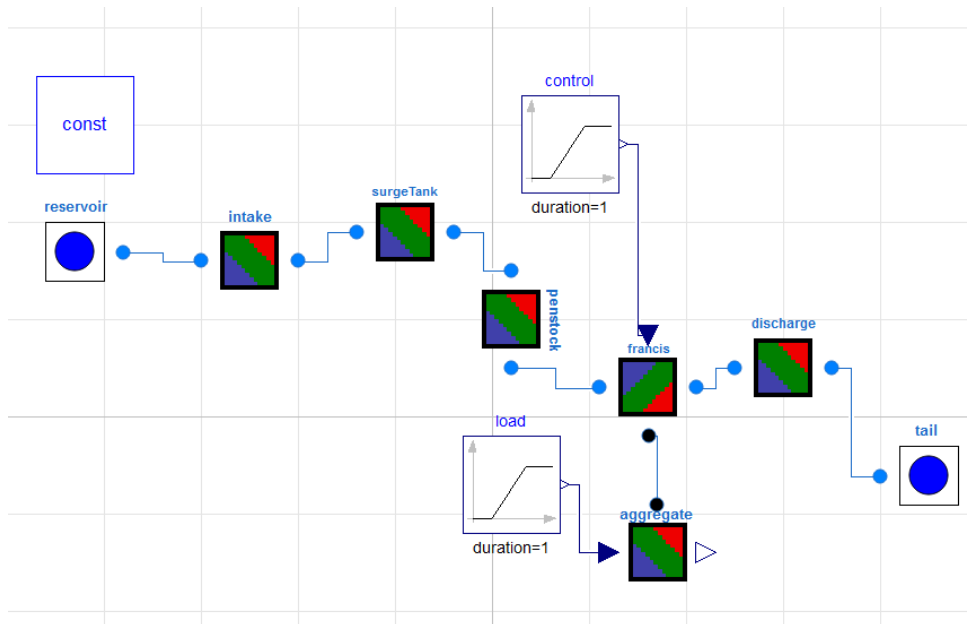
Figure 4.2: The hydropower system with upstream surge tank

The hydropower system with upstream and downstream surge tanks The simulation results of the developed mechanistic model is illustrated on Figure 4.3
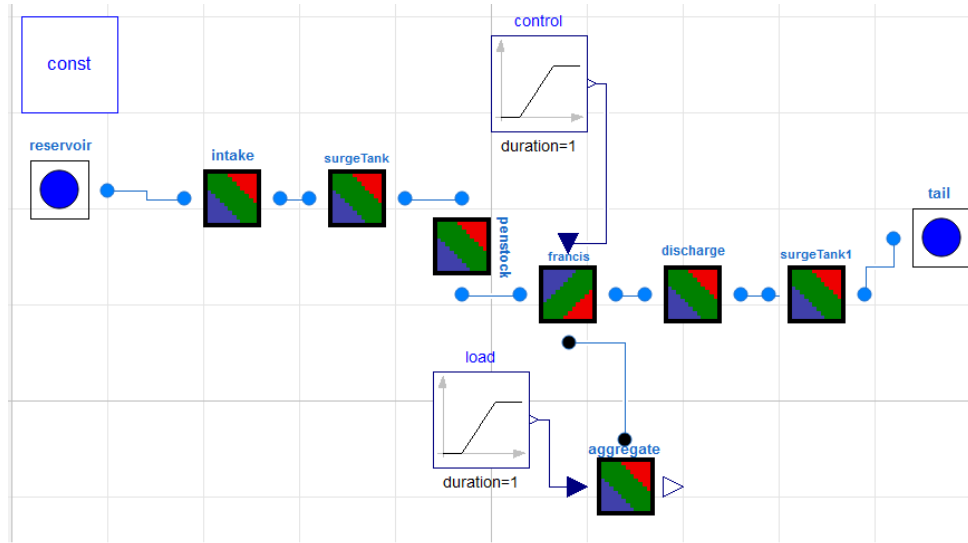
Figure 4.3: The hydropower system with upstream and downstream surge tanks

4.2.2 Hydropower system with Pelton turbine

In this subsection, results of the simulation of a hydropower system with Pelton turbine are given. For the simulation of the developed mechanistic model, study cases from literature sources were used [31, 36, 39] and is given in Table 4.2.2.

Parameter	Value	Units
H	70	m
Q	0,1	$\frac{m^3}{s}$
N	500	rpm

The hydropower system without surge tank   The simulation results of the developed mechanistic model is illustrated on Figure 4.4

The hydropower system with upstream surge tank   The simulation results of the developed mechanistic model is illustrated on Figure 4.5

The hydropower system with upstream and downstream surge tanks   The simulation results of the developed mechanistic model is illustrated on Figure 4.6
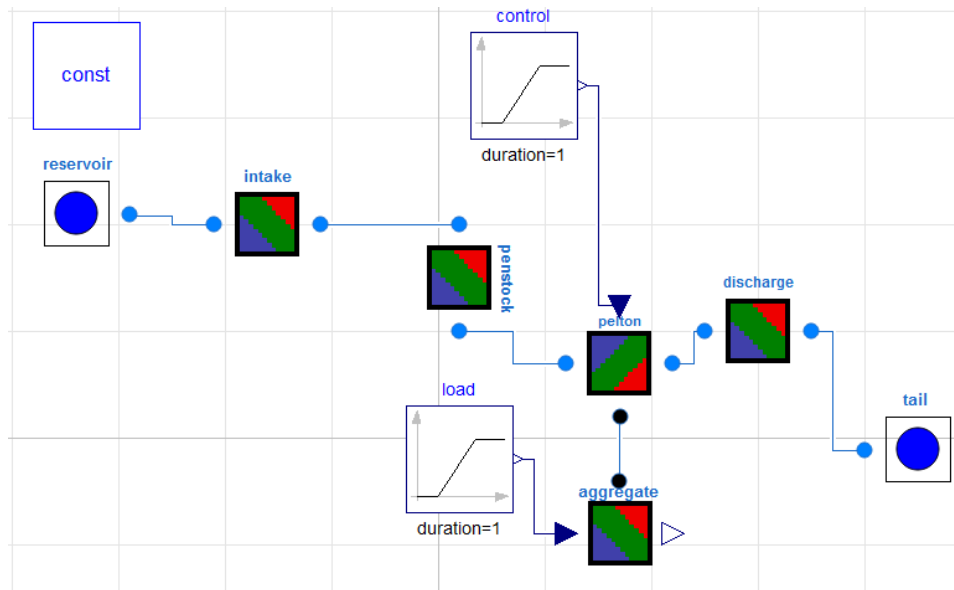
Figure 4.4: The hydropower system without surge tank
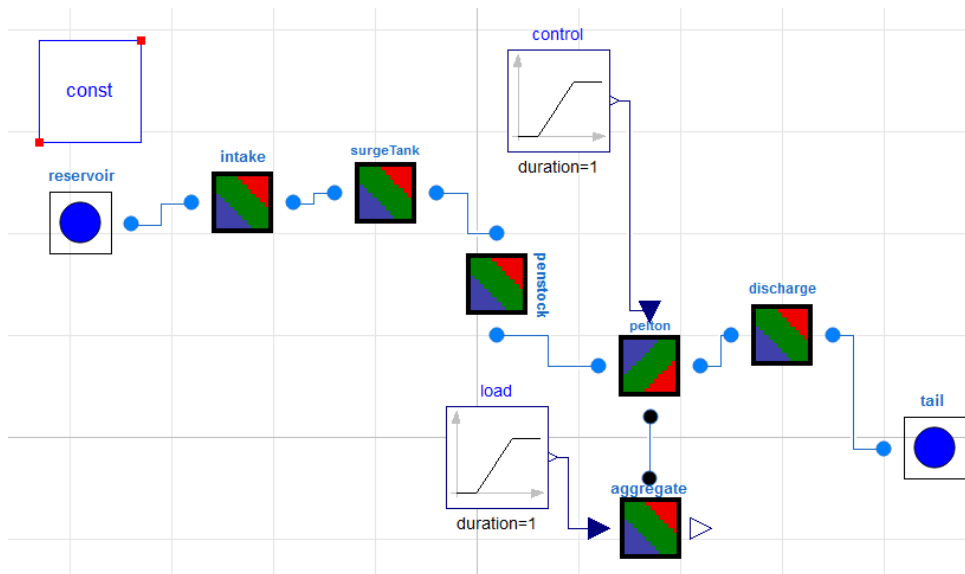
Figure 4.5: The hydropower system with upstream surge tank

4.3 Comparison of mechanistic and look-up table

In the following section the graphical relations of the efficiency of Francis turbine vs. flow rate is illustrated.

The calculated geometry for Pelton and Francis turbines is given in 4.11, 4.3 respect-
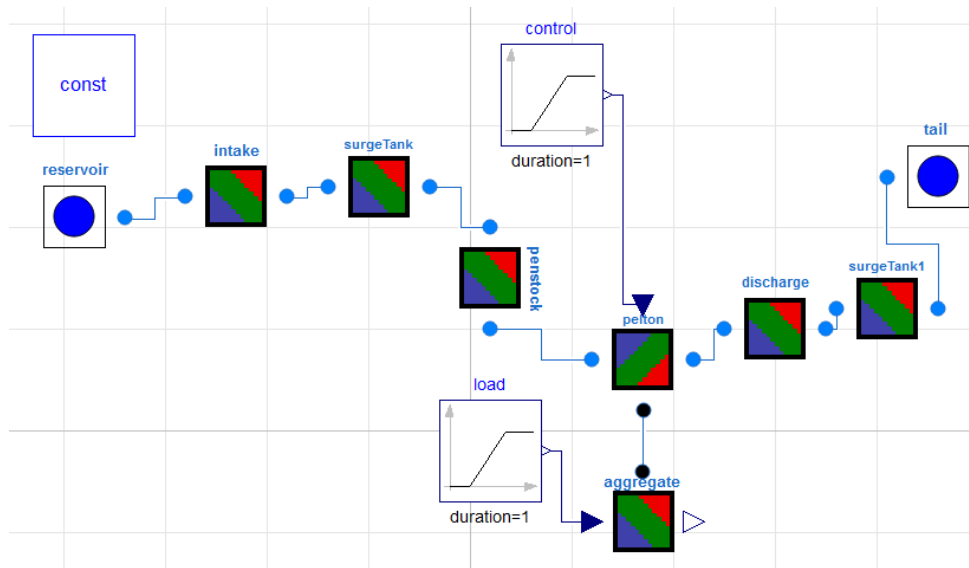
Figure 4.6: The hydropower system with upstream and downstream surge tanks
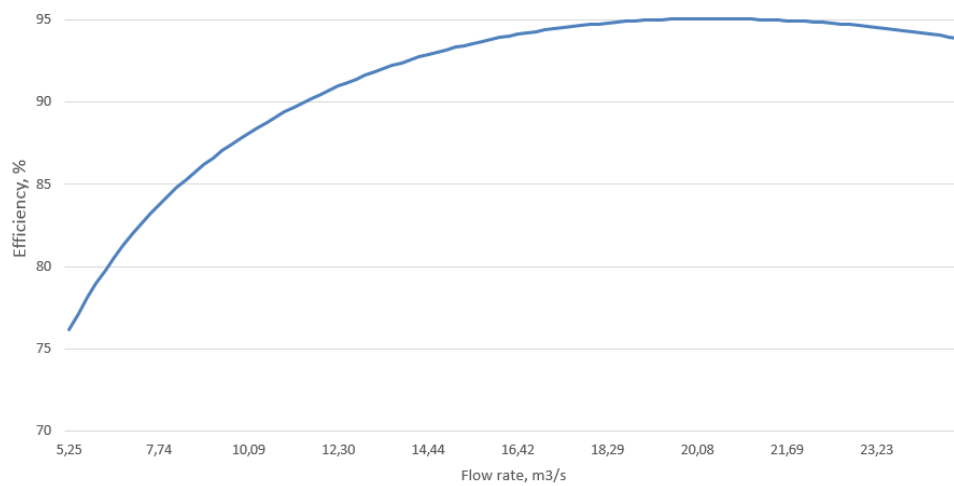
Figure 4.7: The Francis turbine efficiency vs. flow rate

ively.

u_1	c_{u1}	z	d_s	B	D	n	Z_p	$Z_p{}^*$	n^*	D^*
$17,789$	$37,059$	2	$0,041$	$0,133$	$0,346$	$981,67$	$3,056$	5	600	$0,566$

Figure 4.8: The comparison of the obatined results (efficiency) with look-up table

Figure 4.9: The comparison of the obatined results (power) with look-up table

Figure 4.10: The comparison of the obatined results (power) with look-up table

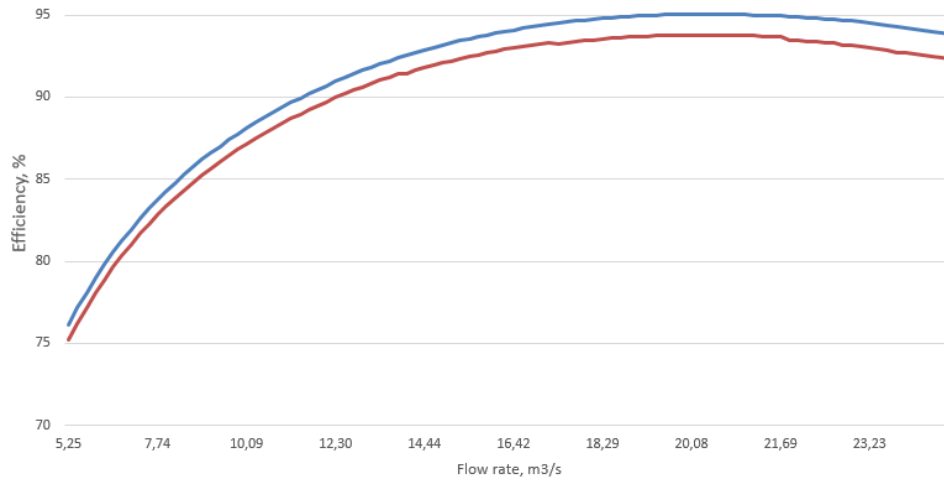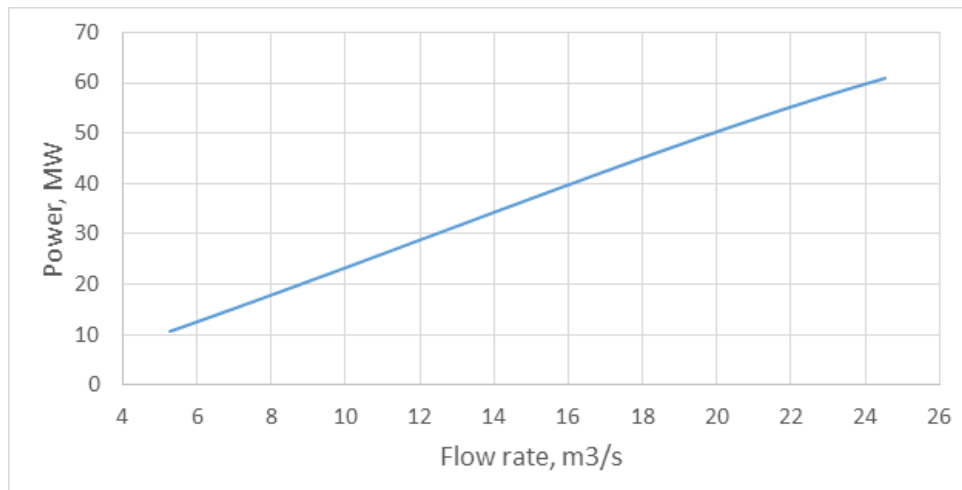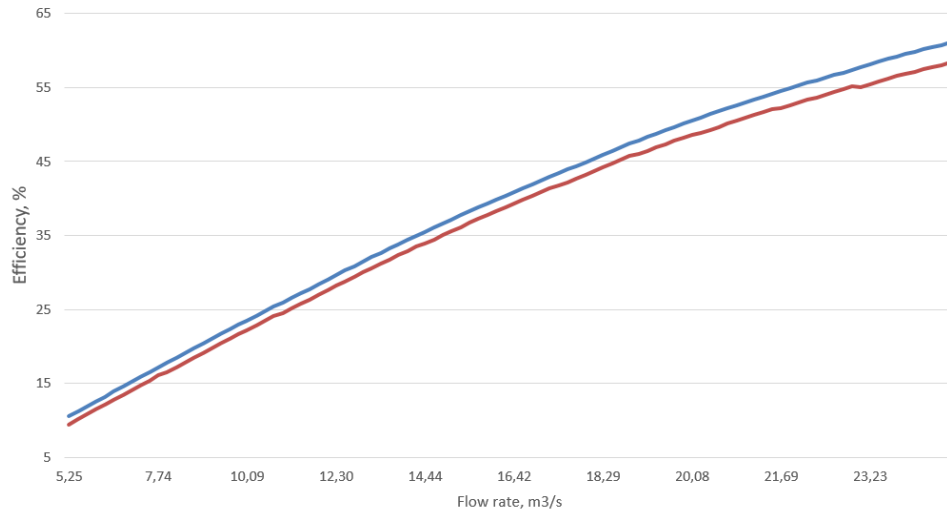| beta2	D2	u2	cm2	cm1	c1	cu1	u1	D1	B1	beta1	u1*	D1*	B1*	cu1*	beta1*	cot_alpha1	alpha1	D0	D0*
147	1,1586	30,3310	19,6972	17,9065	51,4655	48,2499	53,2368	2,0335	0,1815	74,4378	52,7678	2,0156	0,1831	48,5222	76,6613	2,7097	20,2560	2,4024	2,3813
148	1,1735	30,7229	19,1978	17,4526	51,4655	48,4160	53,0542	2,0265	0,1869	75,1170	52,7678	2,0156	0,1879	48,5222	76,3272	2,7802	19,7828	2,3942	2,3813
149	1,1890	31,1268	18,7029	17,0026	51,4655	48,5758	52,8796	2,0199	0,1925	75,7953	52,7678	2,0156	0,1929	48,5222	75,9795	2,8538	19,3109	2,3863	2,3813
150	1,2049	31,5437	18,2118	16,5561	51,4655	48,7298	52,7125	2,0135	0,1983	76,4740	52,7678	2,0156	0,1981	48,5222	75,6169	2,9308	18,8401	2,3788	2,3813
151	1,2213	31,9748	17,7239	16,1127	51,4655	48,8782	52,5525	2,0074	0,2044	77,1543	52,7678	2,0156	0,2035	48,5222	75,2381	3,0114	18,3697	2,3716	2,3813
152	1,2384	32,4216	17,2389	15,6717	51,4655	49,0214	52,3990	2,0015	0,2107	77,8376	52,7678	2,0156	0,2092	48,5222	74,8416	3,0962	17,8994	2,3646	2,3813
153	1,2561	32,8854	16,7560	15,2327	51,4655	49,1596	52,2517	1,9959	0,2174	78,5253	52,7678	2,0156	0,2153	48,5222	74,4257	3,1854	17,4288	2,3580	2,3813
154	1,2746	33,3681	16,2747	14,7952	51,4655	49,2930	52,1103	1,9905	0,2244	79,2191	52,7678	2,0156	0,2216	48,5222	73,9884	3,2796	16,9573	2,3516	2,3813
155	1,2938	33,8715	15,7946	14,3587	51,4655	49,4219	51,9743	1,9853	0,2319	79,9204	52,7678	2,0156	0,2284	48,5222	73,5277	3,3793	16,4846	2,3455	2,3813
156	1,3139	34,3979	15,3149	13,9226	51,4655	49,5465	51,8436	1,9803	0,2397	80,6313	52,7678	2,0156	0,2355	48,5222	73,0410	3,4851	16,0100	2,3396	2,3813
157	1,3350	34,9496	14,8352	13,4866	51,4655	49,6670	51,7179	1,9755	0,2481	81,3535	52,7678	2,0156	0,2432	48,5222	72,5255	3,5978	15,5331	2,3339	2,3813
158	1,3571	35,5295	14,3549	13,0499	51,4655	49,7835	51,5968	1,9709	0,2570	82,0894	52,7678	2,0156	0,2513	48,5222	71,9780	3,7182	15,0533	2,3284	2,3813
159	1,3805	36,1410	13,8732	12,6120	51,4655	49,8963	51,4802	1,9664	0,2665	82,8415	52,7678	2,0156	0,2600	48,5222	71,3948	3,8473	14,5701	2,3232	2,3813
160	1,4052	36,7878	13,3897	12,1724	51,4655	50,0053	51,3680	1,9621	0,2767	83,6126	52,7678	2,0156	0,2694	48,5222	70,7714	3,9862	14,0828	2,3181	2,3813
161	1,4314	37,4744	12,9035	11,7304	51,4655	50,1108	51,2598	1,9580	0,2878	84,4059	52,7678	2,0156	0,2796	48,5222	70,1029	4,1364	13,5907	2,3132	2,3813
162	1,4594	38,2062	12,4139	11,2854	51,4655	50,2129	51,1556	1,9540	0,2997	85,2254	52,7678	2,0156	0,2906	48,5222	69,3832	4,2996	13,0932	2,3085	2,3813
163,20	1,4955	39,1528	11,8209	10,7463	51,4655	50,3311	51,0355	1,9494	0,3155	86,2496	52,7678	2,0156	0,3052	48,5222	68,4418	4,5152	12,4878	2,3031	2,3813
164	1,5215	39,8315	11,4215	10,3832	51,4655	50,4072	50,9584	1,9465	0,3270	86,9615	52,7678	2,0156	0,3158	48,5222	67,7603	4,6731	12,0785	2,2996	2,3813
165	1,5562	40,7419	10,9168	9,9243	51,4655	50,4996	50,8652	1,9429	0,3428	87,8900	52,7678	2,0156	0,3304	48,5222	66,8385	4,8892	11,5594	2,2954	2,3813
166	1,5940	41,7320	10,4049	9,4590	51,4655	50,5888	50,7755	1,9395	0,3603	88,8692	52,7678	2,0156	0,3467	48,5222	65,8271	5,1297	11,0310	2,2914	2,3813
167	1,6354	42,8158	9,8848	8,9862	51,4655	50,6749	50,6892	1,9362	0,3799	89,9089	52,7678	2,0156	0,3649	48,5222	64,7108	5,3996	10,4922	2,2875	2,3813
168	1,6811	44,0116	9,3550	8,5045	51,4655	50,7580	50,6063	1,9330	0,4021	-88,9779	52,7678	2,0156	0,3856	48,5222	63,4704	5,7055	9,9413	2,2837	2,3813
169	1,7320	45,3428	8,8137	8,0125	51,4655	50,8380	50,5266	1,9300	0,4274	-87,7748	52,7678	2,0156	0,4093	48,5222	62,0816	6,0558	9,3767	2,2801	2,3813
170	1,7892	46,8403	8,2592	7,5084	51,4655	50,9149	50,4503	1,9271	0,4568	-86,4596	52,7678	2,0156	0,4368	48,5222	60,5135	6,4624	8,7962	2,2767	2,3813

Figure 4.11: The results of the calculated geometry for Francis turbine

5 Control of the hydropower plant

5.1 Control system

Since a hydropower plants delivers electric power to a grid which they are connected to, there is a requirement to the turbine to keep a synchronous speed of rotation to ensure the grid frequency of 50 Hz [30]. Thus, there is a need of installation of a controller which can maintain the balance between the delivered power and the power demand. This function is in a duty of the governor system which serves for the control and adjustment of the turbine power output [30]. The two main purposes of the governor system are:

1. At any grid load and current conditions in a conduit, the rotational speed of the turbine-generator unit has to be kept stable and constant. [30]

2. If load rejections or any emergency stop occur, according to acceptable limits of the rotational speed rise of the unit and the pressure rise in the conduit, the turbine admission has to be closed.

Principally, the governor system act as:

- In case of deficit of hydraulic power occur in a grid

  In this case the rotational masses decelerate and the speed of rotation decreases. The governor senses a speed deviation from the synchronous speed and gives a signal to change the guide vane position, so that the volume flow increases. Thus, the balance between the delivered power and the power demand is obtained.

- In case of surplus of hydraulic power occur in a grid

  In this case the rotational masses are accelerated, the speed of rotation increases and when the governor senses a speed deviation from synchronous speed, it changes the flow by closing the wicket gates until the hydraulic power and the power demand is balanced [30].

Thus, the main purpose of the governor is to provide stability of a generation unit in case of running on an isolated by keeping of frequency within set deviation limits at any grid load and prevailing conditions in the water conduit. The deviation of the load is a function of the frequency change which depends on the permanent droop setting. Moreover, the governor should close down the turbine admission according to acceptable limits of the

rotational speed rise of the unit and the pressure rise in the water conduit in case of load rejections or emergency stops [30].

Generally, the turbine governor system consists of three main components:

1. The controller - to execute the control processes.

2. Servo system - to amplify that executes the admission changes determined by the controller.

3. The pressure oil supply system – to supply sufficient quantities of pressure oil to the servo system at any time [30].

For a stable operation of the electrical grid, frequency regulation is required. Thus, in case of frequency deviation (increasing/decreasing) in the grid, each power generation unit is obligated to change (reduce/add respectively) a fixed percentage of its total rating output power multiplied by the amount of the change in the grid frequency from/to its output power [21]. It is so-called "speed droop control". The permanent speed droop is set by the grid administration [21]. In Norway this function is performed by Statnett (the permanent speed droop is set to 10
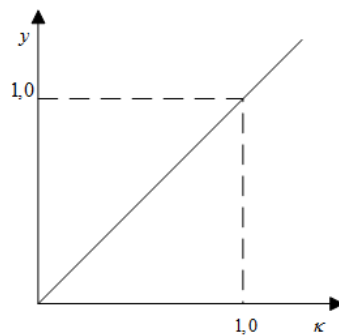

Figure 5.1: The relation between the position of the servo motor and the turbine opening degree

The block diagram of the governor system is given on Figure 5.2. The input reference signal is compared with the measured speed (speed feedback signal).
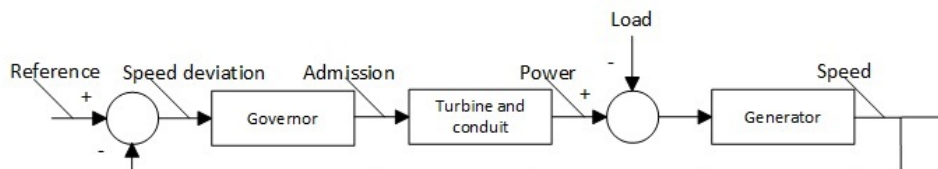

Figure 5.2: The lock diagram of a turbine closed loop governor system

46

By a momentary change in the load a deviation between the generator power output and the load occurs. This deviation causes the unit inertia masses either to accelerate or to decelerate. The output of this process is the speed, which again is compared with the reference.

5.2 Speed droop control

When the frequency deviation (increasing/decreasing) occurs in the grid, there is a requirement for each power generation unit to reduce or add, with respect to the frequency deviation direction, a fix percentage of its total rating output power multiplied by the amount of the change in the grid frequency' from/to its output power [21]. For calculation of the amount of this power, the following equation 5.1 is used:

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

(5.1)

Here, S is a permanent droop, which is a percentage number, set by the grid administration body (for instance, in Norway this is Statnett; speed droop is set to 10 %) [21]. Predominantly, the droop is a decrease in speed setting at the load increases. There are several applications of the droop principle in the control systems.

5.3 Power/frequency Control

One of the stability system requirement is production power with respect to consumption. This leads to flexibility requirement of the production system to changes in consumption and production [21]. The load in the system is continuously variable, which means that the frequency control system is needed [21]. The power/frequency control is performed in to stages:

1. Primary control Primary control implies the speed droop control mentioned in the section above. When the frequency deviation from the optimum value 50 Hz occurs, the speed droop controller is applied automatically to the turbine governor which, in its turn, increases or decreases the guide vane opening wrt the droop control settings.

2. Secondary control After primary control application, the grid has still a constant frequency deviation from optimum. Thus, the secondary control is needed to compensate the deviation by means of the load frequency control. The load frequency control sets higher/lower a set-point to correct the frequency again [21]. Usually,

this type of control is applied in combination with an automatic generation control. The automatic generation control takes into account different generation regions and balances the power production [21].

6 Conclusions

The hydropwoer system modeling is considered in this work. Firstly, the background for the research and its actuality is given in the introduction part. The necessity and profitability of the usage of renewable energy sources is illustrated via statistical data. The main accent is put on the hydro power and the current state of the global usage of them. To expand knowledge in the research achievements within field of the hydro power systems, some previous work concerning modeling and investigation of hydropower system parameters.

To complete understanding of the hydropower system, the main components and possible configuration is described and considered. After components investigation, the conclusion about elements which should be included into the investigated hydro power system is made. Further, the mechanistic model for each element of hydro power system was developed in the form of the differential algebraic equation describing mass, momentum and energy balances. There is a stability requirement to hydropower systems, thence the two main stability criterion are considered.

The simulation of the study cases is following by the mechanistic models development. Dymola software was chosen as a simulation environment because its wide range of advanced tools to simulate hydropower systems. As the study cases were chosen hydropower systems with Francis and Pelton turbines. It was decided to focus on the investigation of impact of the surge tank and its location to the hydropower system stability and efficiency. For that reason,the mentioned above hydropower systems were simulated for cases without surge tank, with upstream located surge tank, with both upstream and downstream located surge tanks. The obtained results of the simulated cases are presented. The obtained results were validated by comparison with hill chart and look-up table. The comparison shows an insignificant deviation between the efficiency curve obtained by simulated data and look-up table, while the deviation with hill charts are more significant. This can be explained by the usage of the specific runner configuration for hill chart development and application of the dimensioning and application of dimensionless parameters. This mean, that, although the hill chart is quite useful tool for fast estimation of the turbine efficiency, but high dependency to the specific geometry makes application of the hill charts to limited. The hill charts can be widely used in case of access to the software for hill charts generation (for instance, HydroHillChart with specific modules for each type of turbines). Otherwise, the mechanistic model gives more realistic results. The usage of the look-up table is easiest method to estimate efficiency of the turbine, but availability

of these tables is quite challenging and not always is available directly. The extended investigation result is presented in the conference paper "Hydropower Systems: Comparison of Mechanistic and Table Look-up Turbine Models". The last chapter presents the main types and requirement to the control system of the hydropower plant. As a potential to the further research I foresee the deepen of the investigation of the control system and development of the comprehensive model of hydro power system considering elastic penstock and water compressibility to obtain more realistic model. Also, it is of interest to make investigation of the efficiency for different turbine configurations.

Bibliography

[1]   *Sustainable Development.* homepage on the Internet. Brussels, Belgium. URL: `http://www.ec.europa.eu/environment/archives/`.

[2]   *Hydropower status report, 2016.* London SM1 1JB (UK): International hydropower association, 2016.

[3]   *Technology Roadmap. Hydropower, 2012.* Paris Cedex, France 75739: International energy agency, 2012.

[4]   *Hydropower.* homepage on the Internet. Oslo, Norway. URL: `http://www.statkraft.com/energy-sources/hydropower/`.

[5]   *The History of Norwegian Hydropower in 5 Minutes.* homepage on the Internet. Oslo, Norway. URL: `https://www.regjeringen.no/en/topics/energy`.

[6]   *Hydropower Sustainability. Final Assessment Protocol. Statkraft, 2013.* Jostedal, Statkraft, Norway: International hydropower association, 2013.

[7]   *Integrating Renewable Electricity on the Grid. A Report by the APS Panel on Public Affairs.* Washington: Public Affairs, 2012.

[8]   *Modelica - A Unified Object-Oriented Language for Systems Modeling. Language Spesification, 2014.* Linkoping, Sweden, 2014.

[9]   *Modelica and the Modelica Association.* homepage on the Internet. Linköping, Sweden. URL: `https://www.modelica.org/`.

[10] Working Group on Prime Mover and Energy Supply Models for System Dynamic Performance Studies. "Hydraulic turbine and turbine control models for system dynamic studies". In: *Transactions on Power Systems* 7.1 (1992), pp. 167–13.

[11] D.G. Ramey and J.W. Skooglund. "A review on hydropower plant models and control". In: *Transactions on power apparatus and systems* 89.1 (1970), pp. 106–7.

[12] O.P. Malik et al. "Frequency measurement for use with a microprocessor-based water turbine governor". In: *IEEE Transactions on Energy Conversion* 6.3 (1991), pp. 361–6.

[13] G. Singh and D.S. Chauhan. "Simplified modeling of hydraulic governor-turbine for stable operation under operating conditions". In: *Elixir International Journal* 39 (2011), pp. 5030–3.

[14] R.A. Naghizadeh, S. Jazebi and B. Vahidi. ''Modeling Hydro Power Plants and Tuning Hydro Governors as an Educational Guideline''. In: *International Review on Modelling and Simulation* 5.4 (2012), pp. 1780–11.

[15] G. Rosenberg. ''Automated Regression Methods for Turbine-Penstock Modeling and Simulation''. In: *American Governor Company* (1991), pp. 1–17.

[16] Yu Zeng et al. ''Nonlinear hydro turbine model having a surge tank''. In: *Mathematical and Computer Modelling of Dynamical System* 19.1 (2012), pp. 12–16.

[17] D. Chen et al. ''Nonlinear dynamical analysis of hydro-turbine governing system with a surge tank''. In: *Applied Mathematical Modelling* 37 (2013), pp. 7611–13.

[18] G. Singh and D.S. Chauhan. ''Dynamic Mathematical Modeling of Hydro Power Plant Turbine''. In: *Journal of Electrical Engineering* 13.1 (2013), pp. 51–5.

[19] J. Yang et al. ''Linear Modeling and Regulation Quality Analysis for Hydro-Turbine Governing System with an Open Tailrace Channel''. In: *Energies 2015* 8 (2015), pp. 11702–16.

[20] J. Garrido, A. Zafra and F. Vázquez. ''Object oriented modelling and simulation of the hydropower plants with run-of-river scheme: A new simulation tool''. In: *Simulation Modelling Practice and Theory* 17.10 (2009), pp. 1748–21.

[21] D. Winkler et al. ''Modelling and Optimisation of Deviation in Hydro Power Production''. In: *Modelica* (2011), pp. 1–10.

[22] P. Podrzaj, M. Miklavcic and A. Bergant. ''Hydro Power Plant Simulator for Control Algorithm Testing''. In: *International Electrotechnical And Computer Science Conference* (2014), pp. 136–4.

[23] M. R. Gomes Zoby and J. I. Yanagihara. ''Analysis of the Primary Control System of a Hydropower Plant in Isolated Model''. In: *Journal of the Brazilian Society of Mechanical Sciences and Engineering* 31.1 (2009), pp. 1–7.

[24] F.de O. Soares e Sousa et al. ''Hydrodynamic loads on a hydraulic turbine wicket gate''. In: *20th International Congress of Mechanical Engineering* 20 (2009), pp. 1–10.

[25] Ch. Nicolet. ''Hydroacoustic modelling and numerical simulation of unsteady operation of hydroelectric systems''. Doctor of Science dissertation. Écublens (Lausanne), Switzerland: EPFL Swiss Federal Institute of Technology in Lausanne, 2007.

[26] C. Nicolet et al. ''High Order Modeling of Hydraulic Power Plant in Islanded Power Network''. In: *IEEE Transaction on Power Systems* 22.4 (2007), pp. 1870–12.

[27] ''Logiciel modulaire pour la simulation et l'étude des systémes d'entraınement et des réseaux électriques''. Doctor of Science dissertation. Écublens (Lausanne), Switzerland: EPFL Swiss Federal Institute of Technology in Lausanne, 1995.

[28]   M. Soni and S. Kaur. "Modeling of Hydraulic turbine for analyzing effect of penstock parameter variation on mechanical power". In: *International Journal of Engineering Research and General Science* 3.3 (2015), pp. 604–8.

[29]   B. Lie, C.E. Agu and L. Vytvytskyi. *Modeling of Dynamic Systems. Project FM 1015.* Porsgrunn, Norway, 2016.

[30]   A. Kjølle. *Hydropower in Norway. Mechanical equipment. Survey.* Trondheim: NTNU Norwegian University of Science and Technology, 2001.

[31]   H. Brekke. *Hydraulic turbines. Design, Erection and Operation.* Trondheim, 2001.

[32]   P. Novak et al. *Hydraulic Structures.* 4th ed. New York, NY 10016: Taylor & Francis, 2007.

[33]   A. Lu Quilisch. "Object Oriented Modelling and Simulation of Kaplan Turbines". Master thesis. Stockholm, Sweden: KTH Royal Institute of Technology, 2008.

[34]   E. Leknes. "Comparison of the Svee and Thoma Stability Criteria for Mass Oscillations in Surge Tanks". Master thesis. Trondheim, Norway: NTNU Norwegian University of Science and Technology, 2016.

[35]   R.H. Svee. "ormler til bestemmelse av svingegrenser og kritiske tverrsnitt". PhD thesis. Trondheim, Norway: Trondheim: Vassdrags og havnelaboratoriet, 1972.

[36]   S.B. Valåmo. "Transient Modelling of Hydropower Plants". Master thesis. Trondheim, Norway: NTNU Norwegian University of Science and Technology, 2016.

[37]   T.K. Nielsen. *Dynamic behaviour of governing turbines sharing the same grid. Technical report.* Trondheim: Kvaerner Energy AS, 1996.

[38]   A. E. Fitzgerald, C. K. Jr and S. D. Umans. *Electric Machinery.* 6th ed. Trondheim: McGraw-Hill Companies, 1993.

[39]   L.A.L. Tenorio. "Hydro Turbine and Governor Modelling. Electric-Hydraulic Interaction". Master thesis. Trondheim, Norway: NTNU Norwegian University of Science and Technology, 2010.

[40]   P. Morgano. "Mathematical Modelling to Simulate Dynamic Effects in Reversible Hydro Systems". Master thesis. Lisbon, Portugal: UTL Technical University of Lisbon, 2010.

[41]   R.A. Nanware, S.R. Sawant and B.T. Jadhav. "Modeling of Hydraulic Turbine and Governor for Dynamic Studies of HPP". In: *International Journal of Computer Applications* 0975.8887 (2012), pp. 6–6.

[42]   J.D. Sharma and A. Kumar. "Development and Implementation of Non-Linear Hydro Turbine Model with Elastic Effect of Water Column and Surge Tank". In: *International Journal of Electrical and Electronics Research* 2.4 (2014), pp. 234–9.

[43]   Yu. Tang. "Francis Turbine and Governor Improved Models Considering Step Closing Law of Guide Vanes for Power System Stability Analysis". In: *Journal of Power and Energy Engineering* 2 (2014), pp. 125–7.

[44] L. Lia et al. "The current status of hydropower development and dam construction in Norway". In: *Hydropower & Dams* 3.3 (2015), pp. 37–7.

[45] D. Gonzales, A. Kilinc and N. Weidman. "Renewable Energy Development. Hydropower in Norway". Seminar paper. Nuremberg, Germany: Georg Simon Ohm University of applied sciences in Nuremberg, 2011.

[46] A. Acakpovi, E.B. Hagan and F.X. Fifatin. "Review of Hydropower Plant Models". In: *International Journal of Computer Applications* 108.18 (2014), pp. 33–6.

[47] N. Kishor, R.P. Saini and S.P. Singh. "A review on hydropower plant models and control". In: *Renewable and Sustainable Energy Reviews* 11 (2007), pp. 776–21.

[48] A.T. Larsen. "Pelton Turbine - Model Test of a Runner". Master thesis. Trondheim, Norway: NTNU Norwegian University of Science and Technology, 2015.

[49] C.K. Sanathanan. "Accurate low order model for hydraulic turbine-penstock". In: *IEEE Transactions on Energy Conversion* 2.2 (1987), pp. 196–5.

[50] B. Lie. *Modeling of Dynamic Systems. Lecture notes.* Porsgrunn, Norway, 2015.

[51] C.V. Davis. *Davis' handbook of applied hydraulics.* Ed. by V.J. Ziparro and Hansen H. 4th ed. Porsgrunn, Norway: McGRAW HILL INC, 1993.

[52] Ø. Antonsen. "Unsteady flow in wicket gate and runner with focus on static and dynamic load on runner". dissertation. Trondheim, Norway: NTNU Norwegian University of Science and Technology, 2007.

[53] L. Vytvytskyi and B. Lie. "Comparison of elastic vs. inelastic penstock model using OpenModelica". In: *SIMS* (2017).

[54] A. Bostan, D. Nedelcu and F. Peris-Bendu. "The Hill Chart Calculation for Pelton Runner Models using the HydroHillChart - Pelton Module Software". In: *ANALELE UNIVERSITĂŢII "EFTIMIE MURGU" REŞIŢA, UEM* 1 (2015), pp. 117–10.

[55] A. Bostan, D. Nedelcu and F. Peris-Bendu. "The Hill Chart Calculation for Francis Runner Models using the HydroHillChart - Francis Module Software". In: *ANALELE UNIVERSITĂŢII "EFTIMIE MURGU" REŞIŢA, UEM* 1 (2015), pp. 117–10.

[56] A. Bostan, D. Nedelcu and F. Peris-Bendu. "The Hill Chart Calculation for Kaplan Runner Models using the HydroHillChart - Kaplan Module Software". In: *ANALELE UNIVERSITĂŢII "EFTIMIE MURGU" REŞIŢA, UEM* 1 (2015), pp. 117–10.

[57] A. Bostan, D. Nedelcu and F. Peris-Bendu. "The Hill Chart Calculation for Bulb Runner Models using the HydroHillChart - Bulb Module Software". In: *ANALELE UNIVERSITĂŢII "EFTIMIE MURGU" REŞIŢA, UEM* 1 (2015), pp. 117–10.

Appendix A

FMH606 Masther's thesis description

FMH606 Master's Thesis

Title: Simulation and control of hydro power plants

HSN supervisor: Bernt Lie, prof., University College of Southeast Norway
Liubomyr Vytvytskyi, PhD student (co-supervisor)

External partner: Skagerak Energi (Ingunn Granstrøm)

Task background:
Energy production from hydropower is very important in Norway and many other countries, and is a sustainable energy source with low CO_2 impact. Models of the "waterway" of hydropower plants ranging from a reservoir to the turbine/generator aggregate is relatively easy to formulate as differential algebraic equations (DAEs), but considerably more complex to formulate in state space form as ordinary differential equations (ODEs). Thus, it is advantageous to encode such models in languages supporting DAEs, e.g., Modelica, and solve the model using, e.g., OpenModelica.

It is of interest to study how models of the waterway can be rigorously formulated as DAEs using mass, momentum and mechanical energy balances, with added algebraic constitutive equations, including models for different types of turbines (e.g., Pelton turbine, Francis turbine, Kaplan turbine). To illustrate the models, it is of interest to develop realistic numerical case studies of, say, two turbine types, with and without surge tank, etc.

It is furthermore of interest to study how the models from Modelica can be used in a study of dynamics and control of the system.

Department of Electrical Engineering, Information Technology and Cybernetics has an on-going co-operation with Skagerak Energi within dynamics, control and optimization of hydro power systems. The department is also involved with Norwegian Hydropower Centre, and has recently become involved in HydroCen: Norwegian Research Centre for Hydropower Technology, which is a Centre for Environment-friendly Energy Research funded by The Research Council of Norway.

Task description:
The following tasks are relevant:
1. Give an overview of the waterway of a hydropower plant, with possible variations depending on different turbines.
2. Describe models for various units in the power plant, e.g., pipes/tunnels filled with water, surge tanks (open or closed), fittings, valves, turbines, etc.
3. Develop 2 numeric case studies for the waterway, implement the models, and simulate the systems.
4. Consider standard methods for controlling the waterway of a hydropower plant, e.g., frequency control or power control.
5. Report the work in the Master's Thesis, and possibly in a suitable conference/journal paper.

Student category: IIA, PT, EET students

Practical arrangements:

The workplace is Campus Kjølnes of University College of Southeast Norway. There will be weekly meetings with the supervisor from January until mid-April, either face-to-face or via Skype, with hand-in of partial reports every 3 weeks.

The thesis work will start January 2, 2017, and the deadline for thesis hand-in is May 15 2017 at 14:00. An oral presentation with examination will take place no later than June 24, 2017.

Signatures:

Student (date and signature): Valentyna Splavska, 25.01.17

Supervisor (date and signature): Bernt Lie, 25.01.17

Appendix B

The abstract for conference paper

Hydropower Systems: Comparison of Mechanistic and Table Look-up Turbine Models

Splavska V., Vytvytskyi L., Lie B.
University College of Southeast Norway, Porsgrunn, Norway
bernt.lie@usn.no
valentyna.splavska@gmail.com

Abstract:

Sustainable energy development implies meeting the energy needs of the future without jeopardizing the life quality of the planet. To achieve this, sustainable energy sources need to be renewable, and hydropower is an undeniable leader among them, according to the latest IEA report.

A hydropower plant, including the waterway, energy transformation block, and the distribution grid, constitutes a complex dynamic system that we must control to operate within constraints. A hydropower plant can be divided into subsystems where several of these belong to the same class, hence an object-oriented modeling language will greatly simplify the process of setting up a model. As an example, various conduits (intake race, penstock, etc.) essentially vary in geometry, slope, friction, etc. The advantage of an object-oriented language is also obvious if we want to study a system of many power plants.

The equation based modeling language Modelica supports differential algebraic equations, and is a good choice for modeling hydropower systems. OpenModelica is one of several free simulation tools based on Modelica; Dymola is an example of a commercial tool. Commercial hydropower libraries are available for Dymola, but a simple, free library is also under development at University College of Southeast Norway.

In this paper, a detailed overview of hydropower system components is given. Components of the system includes intake race, upstream and downstream surge tanks, penstock, turbine and draft tube. We use a case study from the literature for illustration, including a Francis turbine.

Turbine models are available at several levels of detail. Mechanistic models based on physical principles are useful in that they enable simulation of hypothetical systems. Empirical models, on the other hand, require fitting to experimental data.

Accurate mechanistic CFD models are too computationally intensive for transient analysis and control design. Mechanistic models based on the Euler equations are suitable for simulation of hypothetical systems, but may have too constrained model structure to allow for perfect representation. Dimensionless models and hill chart models can be fitted to experimental data, hence are considered empirical models. On the other hand, it is possible to fit "empirical" models to accurate CFD simulations instead of experimental data. These empirical models typically consist of look-up tables for how turbine power efficiency varies with flow rate, control input, etc.

To this end, the paper presents a case study hydropower system, with models implemented in Modelica. For simplicity, we neglect compressibility of water and elasticity of pipe walls: the main aim is to compare a turbine model based on the Euler equations vs. a table look-up model. We also illustrate how surge tanks influence the transients of the system. Because neglecting compressibility and elasticity in water/pipes filters out some pressure transients, the model is not suitable for analysis of cavitation. The research contributes in refining a case study for hydropower systems, and in emphasizing the usefulness of mechanistic turbine models.

Keywords: hydropower system, Modelica, object-oriented modeling, mechanistic model, table look-up model, Francis turbine.

Appendix C

The global hydropower usage. Statistic data

In consonance with IHA prediction, it's expected a doubling of global hydrocapacity up to 2000 GW and global hydroelectricity generation over 7000 TWh by 2050 [2] (Figure C.1).
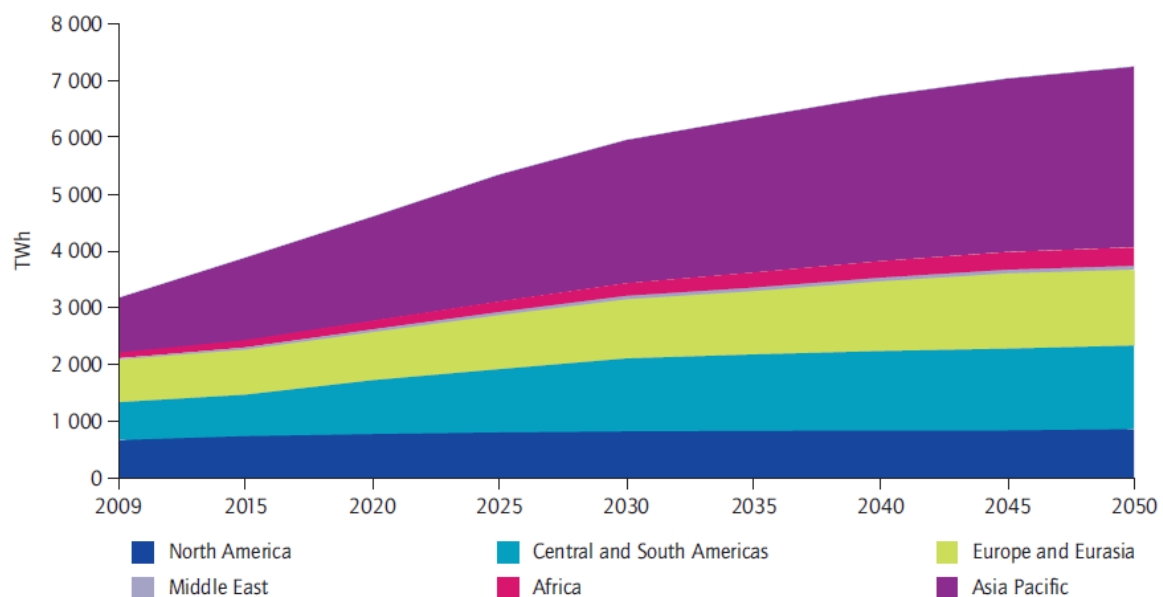
Figure C.1: Hydroelectricity generation till 2050 in the Hydropower Roadmap vision (TWh) [3]

As reported by [3], only during last year an estimated 33,7 GW of hydropower capacity (including 2,5 GW of pumped storage) was put into operation, which in its turn contributed to global installed hydropower capacity rising to 1 212 GW [2]. At the end of 2015 world's hydropower generation reached the level of 3 975 TWh. By the results of 2015, the absolute leader besides of new installed hydropower capacity was China (19,4 GW). Countries with a significant contribution to the extension process of new installed hydropower capacity are Brazil (2, 5 GW), Turkey (2,2 GW), India (1, 9 GW), Iran (1 GW)

and Vietnam (1 GW) [2]. Information about added hydropower capacity generalized over continents is given in Figure C.2.
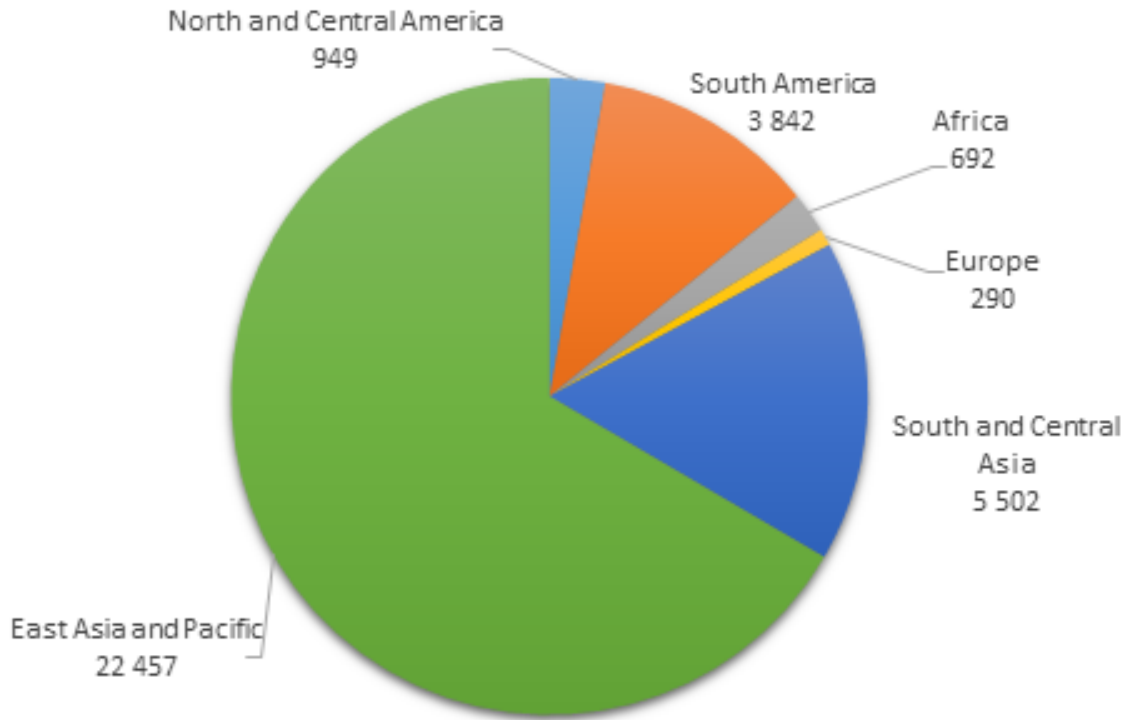
Figure C.2: Newly added hydropower capacity in 2015 generalized over continents, MW

The potential for hydropower capacity additions is still quite ambitious and promising especially in perspective regions in Africa, Asia and Latin America (Figure C.3).

Figure C.3: Regional hydropower technical potential and percentage of undeveloped technical potential (2009) [3]

On European continent Scandinavia and Alpine countries are pioneering and leading regions in the amount of installed hydropower capacity. Generalized picture over installed hydropower capacity in Europe is shown in Figure C.4.

The dynamic of the global hydroelectricty generation for period 1965-2011 is shown in Figure C.5.

Appendix C The global hydropower usage. Statistic data
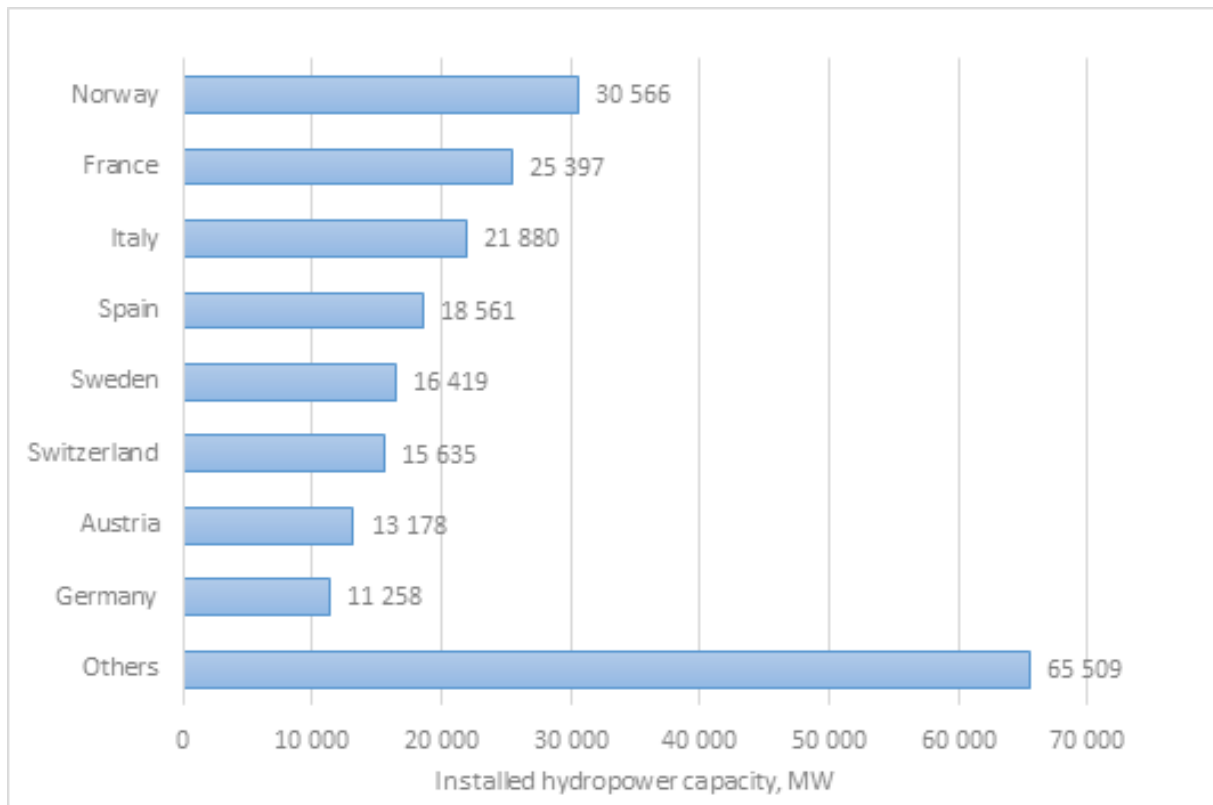
Figure C.4: Installed hydropower capacity in Europe, MW

Figure C.5: The global hydroelectricy generation, 1965-2011

64

Appendix D

The hill charts

The hill chart for Pelton turbine with K461 runner is presented in Figures D.1, D.2.

Figure D.1: The K461 runner hill chart and the matrix of discrete points [54]

The hill chart for Francis turbine with RO75-702 and /// runner is presented in Figures D.3, D.4 .

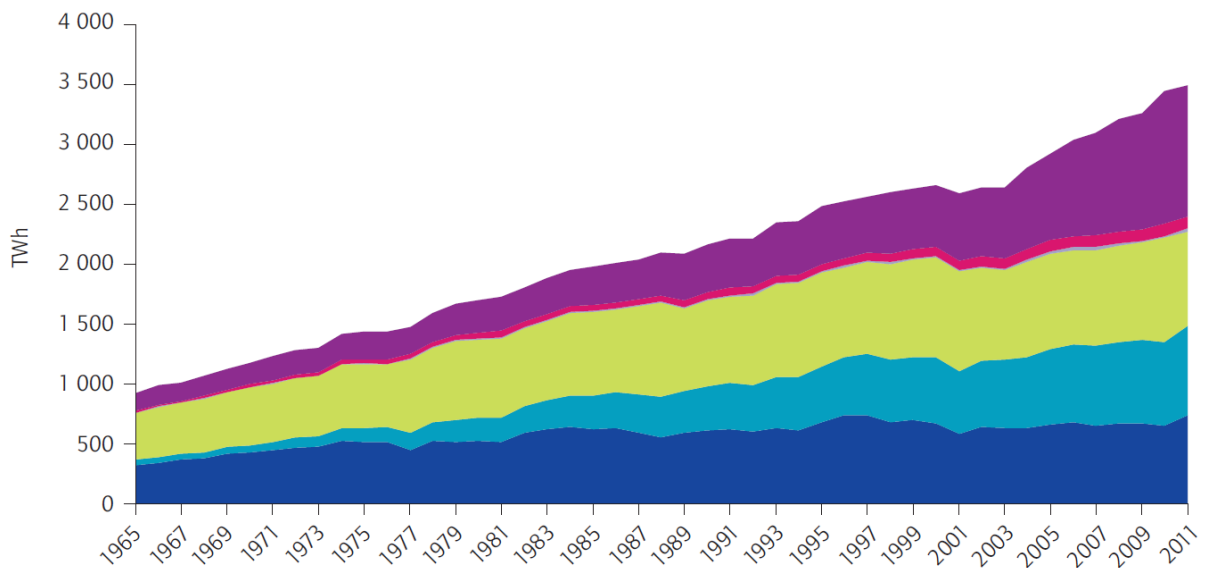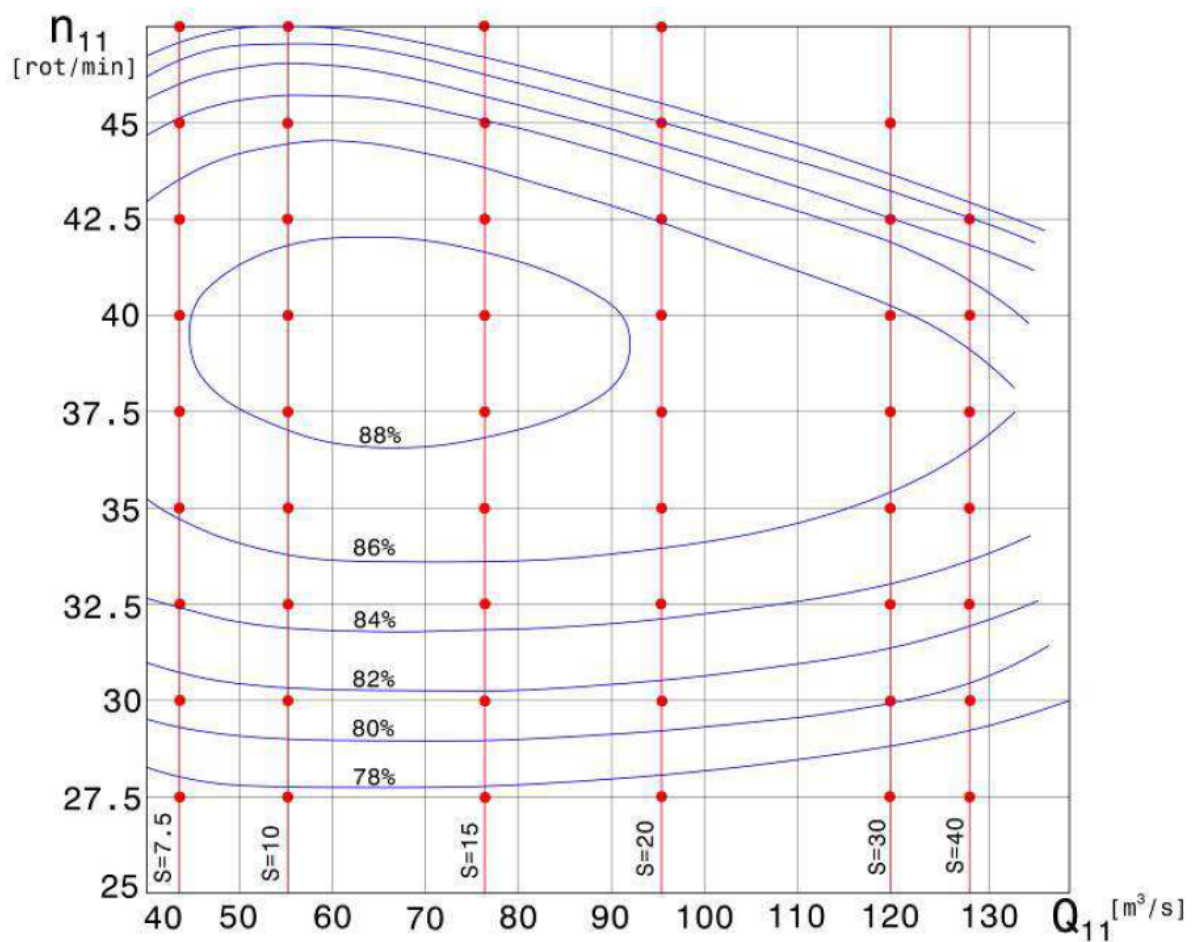| ID punct	S [mm]	Q_{11} [m3/s]	n_{11} [rot/min]	η [%]	ID punct	S [mm]	Q_{11} [m3/s]	n_{11} [rot/min]	η [%]
1	7.5	43.75	27.5	77.40	27	15.0	77.50	47.5	76.50
2	7.5	43.75	30	81.00	28	20.0	96.25	27.5	77.10
3	7.5	43.75	32.5	84.00	29	20.0	96.25	30	81.00
4	7.5	43.75	35	86.20	30	20.0	96.25	32.5	84.30
5	7.5	43.75	37.5	87.50	31	20.0	96.25	35	86.60
6	7.5	43.75	40	87.80	32	20.0	96.25	37.5	87.80
7	7.5	43.75	42.5	86.80	33	20.0	96.25	40	87.60
8	7.5	43.75	45	83.20	34	20.0	96.25	42.5	85.50
9	7.5	43.75	47.5	78.00	35	20.0	96.25	45	80.20
10	10.0	56.00	27.5	77.60	36	20.0	96.25	47.5	73.00
11	10.0	56.00	30	81.30	37	30.0	119.00	27.5	76.00
12	10.0	56.00	32.5	84.40	38	30.0	119.00	30	80.00
13	10.0	56.00	35	86.70	39	30.0	119.00	32.5	83.50
14	10.0	56.00	37.5	88.30	40	30.0	119.00	35	85.80
15	10.0	56.00	40	88.90	41	30.0	119.00	37.5	87.00
16	10.0	56.00	42.5	87.90	42	30.0	119.00	40	85.70
17	10.0	56.00	45	84.20	43	30.0	119.00	42.5	81.00
18	10.0	56.00	47.5	78.50	44	30.0	119.00	45	75.00
19	15.0	77.50	27.5	77.60	45	40.0	129.00	27.5	75.00
20	15.0	77.50	30	81.40	46	40.0	129.00	30	79.00
21	15.0	77.50	32.5	84.70	47	40.0	129.00	32.5	82.50
22	15.0	77.50	35	86.90	48	40.0	129.00	35	85.00
23	15.0	77.50	37.5	88.30	49	40.0	129.00	37.5	86.10
24	15.0	77.50	40	88.50	50	40.0	129.00	40	84.00
25	15.0	77.50	42.5	87.00	51	40.0	129.00	42.5	80.00
26	15.0	77.50	45	82.60					

Figure D.2: The K461 runner hill chart's table [54]

The hill charts are buil.d by using HydroHillChart software with Pelton and Francis modules. The hill charts for bulb and Kanplan turbines are presented in [57] and [56] respectively.
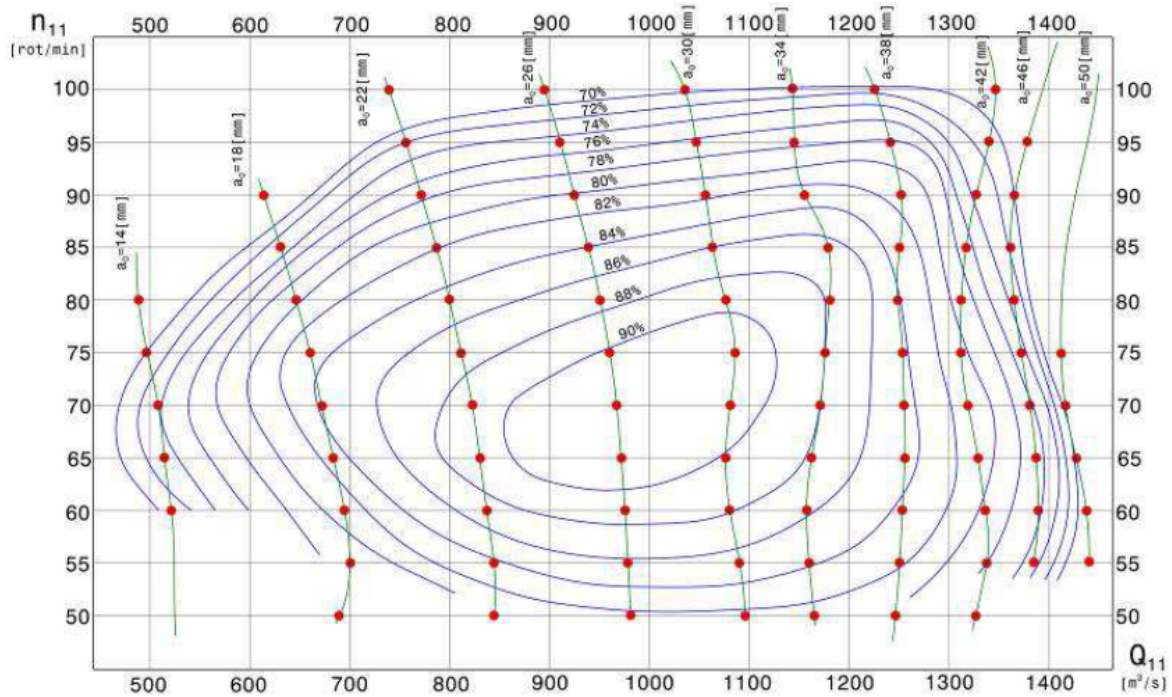
Figure D.3: The RO75-702 runner hill chart and the matrix of discrete points [55]

ID_POINT	n11	Q11	ao[mm]	η (%)	ID_POINT	n11	Q11	ao[mm]	η (%)	ID_POINT	n11	Q11	ao[mm]	η (%)
1	100	740.00	22.00	63.80	32	80	800.00	22.00	84.70	63	65	1077.00	30.00	90.10
2	100	895.00	26.00	67.40	33	80	950.00	26.00	87.40	64	65	1160.00	34.00	87.60
3	100	1040.00	30.00	69.40	34	80	1075.00	30.00	89.20	65	65	1255.00	38.00	84.50
4	100	1145.00	34.00	70.50	35	80	1180.00	34.00	87.70	66	65	1330.00	42.00	81.00
5	100	1225.00	38.00	70.80	36	80	1254.00	38.00	84.00	67	65	1390.00	46.00	76.50
6	100	1348.00	42.00	68.00	37	80	1310.00	42.00	79.00	68	65	1420.00	50.00	70.00
7	95	755.00	22.00	72.00	38	80	1365.00	46.00	73.20	69	60	525.00	14.00	71.00
8	95	912.00	26.00	74.80	39	75	497.00	14.00	70.00	70	60	695.00	18.00	81.00
9	95	1048.00	30.00	76.50	40	75	660.00	18.00	82.80	71	60	840.00	22.00	87.00
10	95	1146.00	34.00	77.80	41	75	814.00	22.00	87.20	72	60	975.00	26.00	89.00
11	95	1245.00	38.00	78.00	42	75	960.00	26.00	90.20	73	60	1082.00	30.00	88.10
12	95	1340.00	42.00	71.20	43	75	1080.00	30.00	91.40	74	60	1158.00	34.00	86.30
13	95	1382.00	46.00	67.00	44	75	1175.00	34.00	88.30	75	60	1253.00	38.00	83.60
14	90	612.50	18.00	66.20	45	75	1255.00	38.00	84.40	76	60	1335.00	42.00	79.90
15	90	770.00	22.00	77.00	46	75	1312.00	42.00	80.40	77	60	1390.00	46.00	75.80
16	90	926.00	26.00	80.10	47	75	1375.00	46.00	74.80	78	60	1430.00	50.00	68.10
17	90	1057.00	30.00	81.90	48	75	1412.00	50.00	67.20	79	55	700.00	18.00	78.50
18	90	1157.00	34.00	83.00	49	70	508.00	14.00	73.70	80	55	845.00	22.00	83.70
19	90	1251.00	38.00	81.20	50	70	672.00	18.00	83.90	81	55	978.00	26.00	85.80
20	90	1330.00	42.00	73.80	51	70	825.00	22.00	88.90	82	55	1090.00	30.00	85.30
21	90	1365.00	46.00	70.00	52	70	967.00	26.00	92.50	83	55	1163.00	34.00	84.10
22	85	630.00	18.00	73.00	53	70	1080.00	30.00	91.50	84	55	1250.00	38.00	82.00
23	85	786.00	22.00	81.70	54	70	1168.00	34.00	88.20	85	55	1335.00	42.00	78.50
24	85	940.00	26.00	84.10	55	70	1256.00	38.00	84.60	86	55	1383.00	46.00	74.20
25	85	1065.00	30.00	86.00	56	70	1320.00	42.00	81.00	87	55	1430.00	50.00	66.00
26	85	1179.00	34.00	86.40	57	70	1383.00	46.00	76.30	88	50	690.00	18.00	74.00
27	85	1253.00	38.00	83.00	58	70	1412.00	50.00	70.00	89	50	845.00	22.00	79.50
28	85	1315.00	42.00	76.90	59	65	516.00	14.00	73.30	90	50	980.00	26.00	81.50
29	85	1360.00	46.00	71.70	60	65	683.00	18.00	83.00	91	50	1095.00	30.00	81.60
30	80	485.00	14.00	65.00	61	65	833.00	22.00	89.00	92	50	1170.00	34.00	81.00
31	80	647.00	18.00	79.70	62	65	972.00	26.00	91.80	93	50	1247.00	38.00	79.40
										94	50	1325.00	42.00	75.00

Figure D.4: The RO75-702 runner hill chart's table [55]