UNIVERSITÀ DEGLI STUDI DI PADOVA

UNIVERSITA' DEGLI STUDI DI PADOVA

**Dipartimento di Ingegneria Industriale DII**

Corso di Laurea Magistrale in Energy Engineering

# *Transient analysis for installation of a hydraulic turbine in existing water conveyance infrastructure*

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# Abstract

La ricerca di seguito descritta mira allo studio dei transitori idraulici in un sistema di adduzione di acqua potabile realmente esistente in Arabia Saudita. Le premesse indicano che siamo al cospetto di costanti e variabili che devono essere attentamente analizzate e modificate, per rendere il modello il più reale possibile. Per questo tipo di studio sono stati impiegati e confrontati due software: il primo è l'open-software OpenModelica, sviluppato dai ricercatori della University of South-Eastern Norway (USN), il secondo è il software SIMSEN il quale rappresenta uno dei migliori mezzi per lo studio dei transitori idraulici. Varie prove e vari modelli sono stati sviluppati prima di arrivare agli schemi ottimizzati ivi presentati. Dai parametri di partenza, si è cercato di sviluppare i modelli in modo più fedele possibile per poter essere in grado di fare una comparazione tra i software e ricavarne la bontà di calcolo. Mettendo a confronto l'insieme, si è giunti alla conclusione che OpenModelica ha dei limiti che non permettono di affrontare un calcolo di transitori in modo dettagliato e valido, mentre SIMSEN è molto più sensibile ai dati di input e, conseguentemente, offre una migliore rappresentazione della realtà.

# Introduction

The present study aims to analyze at preliminary stage the installation of a turbine inside an existing water supply system that conveys desalinated seawater from a desalination plant in Abha, Asir region, Saudi Arabia. Desalinated seawater is used for municipal water and industrial water. It will cover almost 50% of total water production by 2025 for the Asir region.

In a scenario where the water demand as well as energy demand is continuously growing the chance to exploit already existing infrastructure has great economic advantages because the erections costs are limited to those of the electromechanical equipment. The so called “Conduit hydropower” refers exactly to this: hydropower turbine is installed inside the existing pipeline, in specific locations where there are favorable discharge and head for power output maximization. The most preferred locations are usually in correspondence of PVR (Pressure Reduction Valves). PVR are used in water transmission systems to dissipate energy and thus to control the operating pressure of the system itself. The most common layout to exploit this pressure drop is to have a hydropower turbine installed in parallel to PVRs in order to exploit this drop of pressure that would be otherwise lost.

This in parallel installation is quite straightforward and does not have much impact on the existing system layout. Different is the case for the operating conditions: it is fundamental to verify that the turbine does not affect the standard operating conditions of the water transmission system or, even worse, damage the infrastructure itself. Once that the turbine design parameters (design discharge, design head and velocity) have been identified by the turbine supplier, the very first preliminary study that is carried out is the transient analysis on the worst scenario which is the ESD (Emergency Shut Down).

The turbine is disconnected from the electrical grid due to any reason. In this condition, the turbine is no longer coupled to the generator, and thus the effect of generator inertia is suddenly zero. The turbine starts to increase its rotational velocity until it reaches its runaway speed. This causes a water load rejection that creates a water hammer on the upstream penstock. Even at very preliminary design it is fundamental to estimate the maximum pressure increase related to ESD in order to verify if the turbine is compatible with the maximum allowable pressure of the infrastructure pipes. The alternative is to have a very high probability of the penstock collapsing due to the overpressure related to turbine ESD.

The present study investigates the limits and capabilities of an open-source library (OpenHPL) to study transient behavior of hydropower plant. The investigation is carried out in comparison with the SIMSEN software which is the state-of-the-art commercial software used for transient analysis.

This study and the related activities and software has been carried out with the support of ZECO hydropower company: an Italian turbine manufacturer active since 1960. The results of this analysis might be of interest for researchers and hydropower developers in choosing the most suitable software for the analysis of ESD transient phenomenon.

# Chapter 1: Theory Background

## Classification of Flow

The motion of a fluid in a pressure system can be influenced by particular situations or maneuvers that produce oscillatory phenomena. If the flow conditions (such as velocity and pressure) are constant over time, the flow is steady. In real life, slight changes in velocity and pressure always occur, but if the mean values are constant, then the flow is accepted as steady flow. If, over the time, velocity and pressure are not maintained constant, the flow is steady-oscillatory. In this case the same flow conditions developed in fixed-time intervals called “period”. In hydroelectric plants, the demand for the service leads to the need to vary the power supplied by the plant by modifying the flow rate absorbed by the hydraulic turbines to satisfy the corresponding request almost instantaneously. Hydraulic transient is an unsteady flow particular state within a system, that represents the link from a condition of steady flow to another one.

### *Water hammer Description*

As a result of the maneuvers that create the variations, a succession of disturbances is produced in the system (overpressures and depressions compared to the steady state pressure) which propagate very quickly along the pipeline starting from the section in which the maneuver was carried out. The study of this phenomenon, known as water hammer, can be done, within certain limits, using the hypotheses that the fluid and the conduct are infinitely rigid (inelastic hypothesis). In this case, the celerity of the perturbation propagation is infinite. The opposite, in the more general case, is

considering the influence of the elastic properties of the fluid and conduct (elastic hypothesis). In this case, the celerity of the perturbation propagation is high but finite.

Water hammer is the change in flow properties due to a disturbance in the pipe systems. There are many causes of the water hammer. Common reasons for water hammer are:

- Valve operations, such as closing/opening;
- Pump operations, such as switching on/switching off;
- Hydraulic turbine operations;
- Change in water elevation of a reservoir;
- Waves on the surface of a dam reservoir due to earthquake, winds or landslides;
- Power failures in the system;
- Emergency closure of the units.

Therefore, to prevent load fluctuations from damaging the system, it is practically necessary to carry out maneuvers that do not produce excessive stress, which can cause:

- damage and break of the regulating organs;
- damage of pumps and turbines;
- separation of the liquid columns.

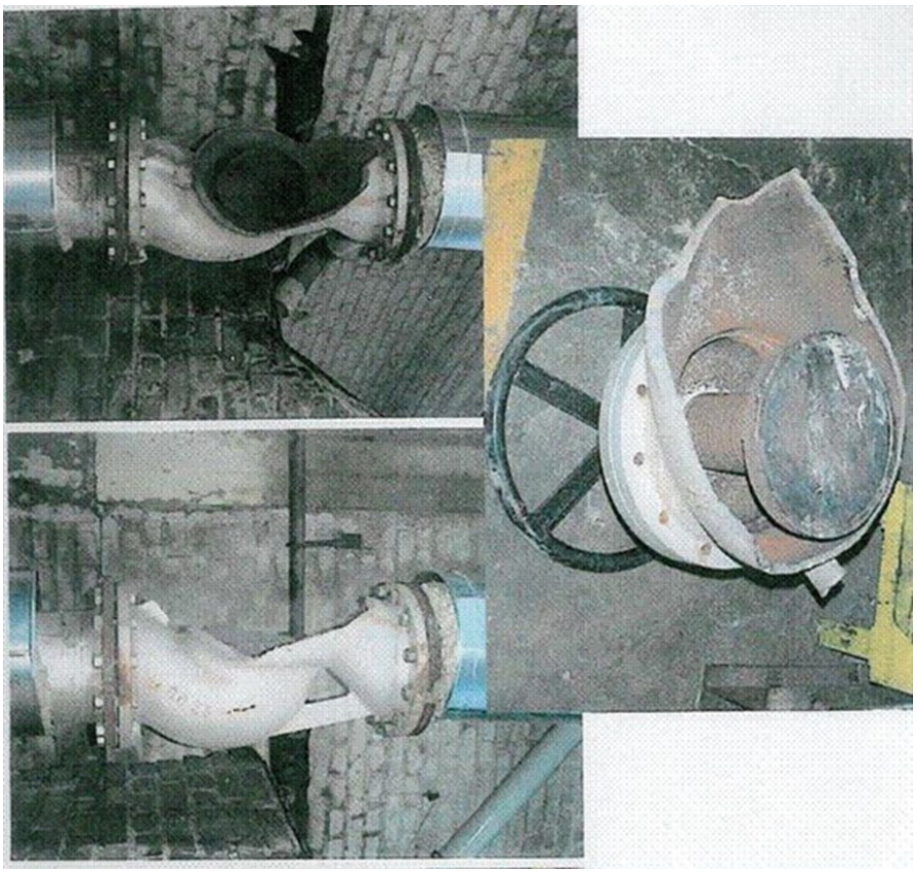

*Figure 1.1: Damages caused by water hammer effect in a pipeline*

*One dimensional introduction theory: forced conduct*

*Water hammer's elastic theory*

Consider a Pipe with diameter d and thickness e constants. Let E and Em also be the elastic moduli of the water and of the material with which the pipe is constructed, respectively. In the steady-state situation, the flow rate Q flows with an average speed $v_0$. We want to determine the value of the overpressure $\gamma\Delta h$ that is produced for a complete and instantaneous closure at the end of the pipeline. Focusing attention on a section of pipe of length x, suppose that we make an abrupt and instantaneous stop of its downstream face such that the velocity passes from $v_0$ to 0. The change in kinetic

energy must be equal to the deformation work of the fluid x section and the outer diameter due to the unit overpressure γΔh that is created.

Indicated by: Δx the elastic displacement of the x-section; p=γΔh the unit overpressure and with P= γΔh· A the force applied to the area A;

Change in kinetic energy: $\Delta E_c = \gamma \mathrm{A} \mathrm{x} \frac{v_0^2}{2g} = \gamma \frac{\pi d^2}{4} x \frac{v_0^2}{2g}$

X-section deformation work: $W_f = \frac{1}{2} P \cdot \Delta x = \frac{1}{2} \gamma \Delta \mathrm{h} \frac{\pi d^2}{4} \frac{\gamma \Delta h \cdot x}{E}$

Diameter deformation work: $W_i = \frac{1}{2} F \cdot \Delta s = \frac{1}{2} \frac{pd}{2} \cdot x \cdot \Delta s = \frac{1}{2} \frac{\gamma \Delta h \cdot d}{2} \cdot x \cdot \frac{\gamma \Delta h \cdot d}{2 e E_m} \cdot \pi d$

From the condition: $\Delta E_c = L_f + L_i$

You get: $\Delta h = \frac{v_0}{\sqrt{\gamma g \left(\frac{1}{E} + \frac{d}{e E_m}\right)}} = \frac{v_0}{g \sqrt{\rho \left(\frac{1}{E} + \frac{d}{e E_m}\right)}}$

Therefore, the overpressure $\Delta h$ is directly proportional to the average velocity $v_0$.

The speed a, with which the overpressure wave propagates, can be deduced from:

$$a = \frac{dx}{dt} = \frac{g \Delta h}{v_0}$$

So:

$$a = \frac{1}{\sqrt{\rho \left(\frac{1}{E} + \frac{d}{e} \cdot \frac{1}{E_m}\right)}}$$

Which for a sudden stop becomes:

$$\Delta h = \frac{a v_0}{g}$$

Interestingly, for an infinitely rigid duct material, the speed of propagation becomes $a = \sqrt{E/\rho}$: since for the water at 10°C is E=2· $10^9$Pa e ρ=1000$kg/m^3$, you get a≅ $1400\, m/s$. The terms $\rho d/eE_m$ therefore represents the contribution linked to the elasticity of the material, which contributes to attenuating the value of a.

Let's consider a system consisting of an upstream tank, a pipeline and a downstream valve, with water in steady motion conditions. The hypothesis of instantaneous closure of the valve is made.

By doing that, the liquid column moving inside the pipeline is in front of the blocked road. As a consequence, it is progressively coming to a halt. This leads to the transformation of the kinetic energy possessed by the water into elastic compression energy. The overpressure wave that is generated will propagate along the entire length of the pipeline with speed *a*.

At the moment of closing at *t=0*: the section of liquid column stops, passing from an initial velocity $v=v_0$ to a final velocity *v=0*. The piezometric load increases from an initial value $H=H_0$ to a final value $H=H_0+\Delta H$. As consequence, the pipe undergoes elastic deformation.

- In the following moment, between time *t=0* and time *t=L/a*, the liquid column is progressively stopped along the entire pipeline and the consequent pressure wave of intensity *ΔH* propagates from the closing section to the downstream tank with speed a.

- At time $t=L/a$, the overpressure wave reaches the upstream tank. The pipe turns out to be all dilated with water inside still and compressed.
- Between $L/a<t<2L/a$, a negative pressure wave of intensity $-\Delta H$ propagates inversely. Consequently, a negative flow moves towards the tank with velocity $v=-v0$ and the pipeline returns to its initial dimensions.

The time $\tau=2L/a$, necessary for the pressure disturbance produced at the obturator to return to the shutter itself after being reflected from the tank is a time characteristic which has, as we will see, considerable importance. Such time characteristic is called the "rhythm" of the conduct and is normally indicated with $\tau$.

The characteristic time of the pipeline represents the time it takes for the pressure wave to reach the upstream tank and return to the valve. During this period, the pipeline is subjected to maximum pressure increase.

- Between $2L/a<t<3L/a$, along the pipeline, a negative pressure wave of intensity $-\Delta H$ propagates towards the tank and the liquid column progressively stops. As a result of the reduction of the piezometric load, the pipe undergoes a negative elastic deformation.
- At time $t=3L/a$, the negative overpressure wave reaches the tank. The pipe is all in depression and the water inside is still. At this time, the liquid level of the tank is higher than the piezometric load in the pipeline. A new state of instability has arisen.
- Between $3L/a<t<4L/a$, along the pipeline, a positive pressure wave of intensity $\Delta H$ propagates towards the valve. As a result of the increase in piezometric load, the pipeline returns to its initial size and a positive flow is established with velocity $v=v_0$ from the tank to the valve.

- At time $t=4L/a$, the positive pressure wave arrives at the valve. At this moment, the system is in its initial condition. This is the period necessary for the system to return to its initial condition after the initiation of the disturbance. In the absence of pressure drops, since the valve is closed, the phenomenon would be repeated identically in the same way.

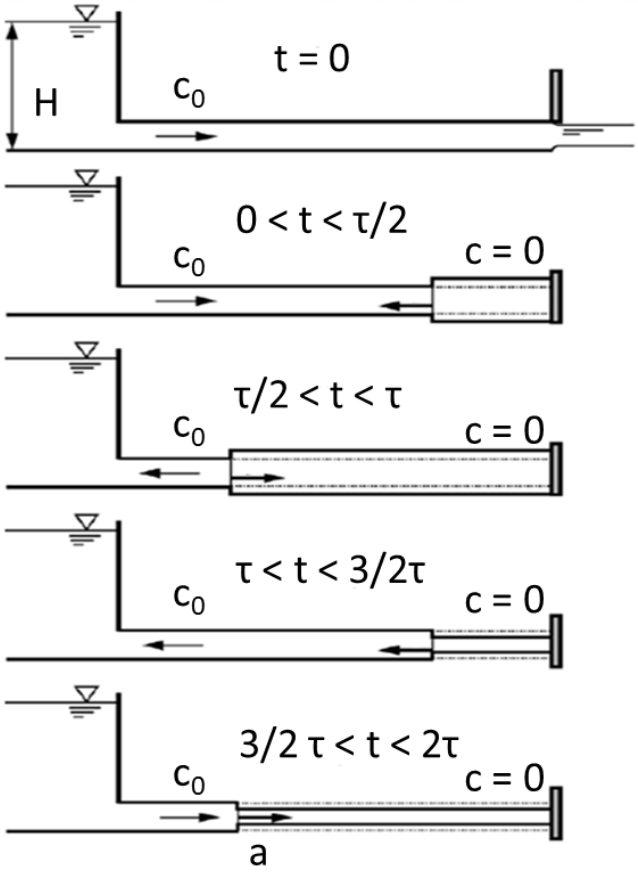


*Figure 1.2: Pressure waves for a shut down*

The first measure to be taken, in order to keep the overpressure value within certain limits, is to carry out gradual maneuvers to close the shutter. Consider a closing maneuver that decreases the flow rate to zero in a linear manner over time. The effects that the corresponding pressure variations may have on the flow rate itself should be considered negligible. If *tc* is the closing time, two cases can be distinguished in relation to the time $\tau = 2L/a$ (characteristic time):

- $t_c < \tau$ called quick closure
- $t_c > \tau$ called slow closure

If the closing time is shorter than the characteristic time, it is called direct water hammer:

$$\begin{cases} t_c \leq \tau = \dfrac{2L}{a} \Rightarrow \\ \Delta H = \Delta H_{max} = \dfrac{a \cdot c}{g} = \dfrac{a \cdot Q}{g \cdot A} \end{cases} \quad Joukowski's\ formula$$

If the closing time is longer than the characteristic time, it is referred to as indirect or reduced water hammer:

$$\begin{cases} t_c > \tau = \dfrac{2L}{a} \Rightarrow \\ \Delta H : \Delta h_{max} \approx \tau : t_c \\ \Delta H = \dfrac{2 \cdot L \cdot c}{g \cdot t_c} \end{cases} \quad Michaud's\ formula$$

# Chapter 2: The project description

The project analyzed herein is a good example of water transmission operating company taking advantage of the existing structure in order to recover hydropower energy. The design concept aims to exploit the energy dissipated by the valves at the end of the pipeline, by inserting a turbine directly into the network, or bypassing it, using the synchronous exhaust scheme. First of all, an initial idea has been developed from the vendor clarifications which provides the guidelines to be applied to the project as a whole.

## 2.1 The site characteristics

The site is located in Abha, Asir Region, Saudi Arabia, at about 2170 meters above the sea level. The desalinization plant is the Shuqaiq Plant, located about 100 km South-West from Abha, facing the Red Sea.

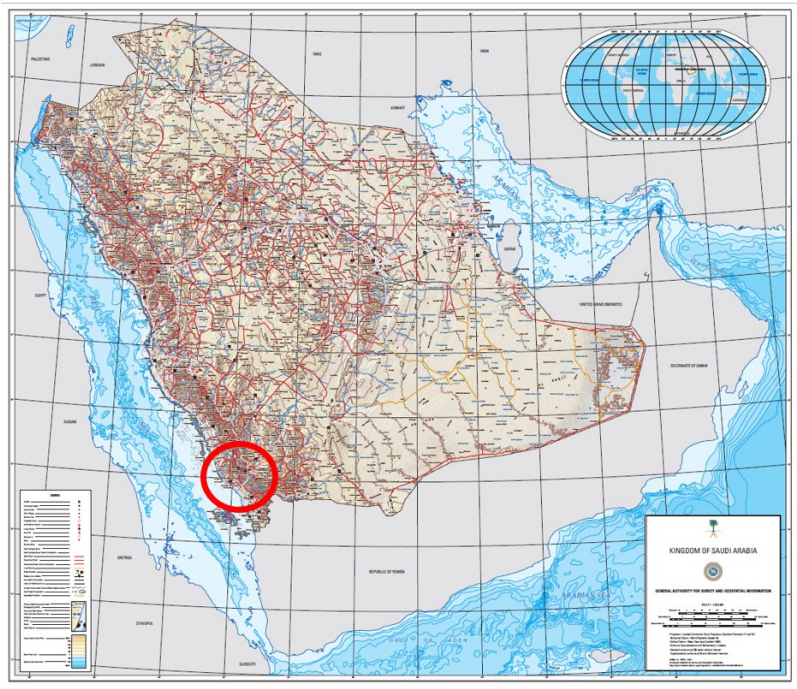


*Figure 2.1: Saudi Arabia and the location of Abha, in the red circle*

In particular, the scope is to study a branch of the system that carries the water from the desalinization plant to the city through stainless steel pipes whose length is 4550 meters. The water then passes through a control valve shaft station and is then stored in an existing reservoir.

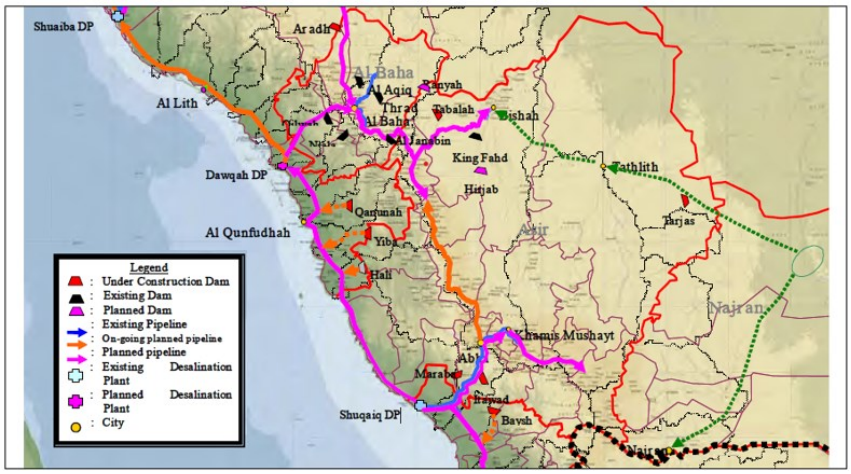


*Figure 2.2: Dams and Desalination Plants in Asir Region*

*Figure 2.3: Layout of the PRV control room and downstream reservoir*

The potable water that flows within the system has a temperature equal to 30°C, density of 995,65 kg/m$^3$ and pressure of 1 bar. Moreover, the location of the plant is near the Equator, so the change in the acceleration of gravity is not negligible.

| Latitudine | 0 m s.l.m. | 1000 m s.l.m. | 2000 m s.l.m. | 3000 m s.l.m. | 4000 m s.l.m. |
|---|---|---|---|---|---|
| 0 | 9.78 | 9.777 | 9.744 | 9.771 | 9.768 |
| 10 | 9.782 | 9.779 | 9.776 | 9.773 | 9.77 |
| 20 | 9.786 | 9.783 | 9.78 | 9.777 | 9.774 |
| 30 | 9.793 | 9.79 | 9.787 | 9.784 | 9.781 |
| 40 | 9.802 | 9.799 | 9.796 | 9.792 | 9.789 |
| 50 | 9.811 | 9.808 | 9.804 | 9.801 | 9.798 |
| 60 | 9.819 | 9.816 | 9.813 | 9.81 | 9.807 |
| 70 | 9.826 | 9.823 | 9.82 | 9.817 | 9.8147 |

*Table 2.1: gravity acceleration in m*s^(-2)*

Considering a latitude of 18,19°N, the formula for the fixed gravity is:

$$g = 9.7803 \cdot (1 + 0.0053 \sin^2(L)) - 3 \cdot 10^{-6} h$$

(where “h” is the elevation above the sea level).

The final acceleration of gravity constant is set to 9.786 m/s$^2$.

The atmospheric pressure changes with elevation too. The atmospheric pressure for measurements is expressed as a function of the altitude according to ISO2533 ”Standard Atmosphere”:

$$p_{atm} = 1.01325 \cdot (1 - 2.558 \cdot 10^{-5} \cdot z)^{5.255}$$

Where “z” is the elevation above the sea level, which is 2170 meters for the project site.

## 2.2 The turbine

In order to preliminary identify the turbine that must be installed in the system, the following project data provided by the Client have been used:

- Current flow: 4166,7 $m^3/h$
- Penstock material: stainless steel
- Penstock length: 4550 m
- Penstock diameter: 36'' (=914.4 mm)
- Inlet pressure: 15.5 barg
- Outlet pressure: 0.9 barg
- Nominal head: 149.5 m

The generator must be considered to be installed indoors without air conditioning, in a design ambient of 55°C, with a humidity up to 100%. It must satisfy standard IP55. It will be connected to a 13.8 kV ring main unit.

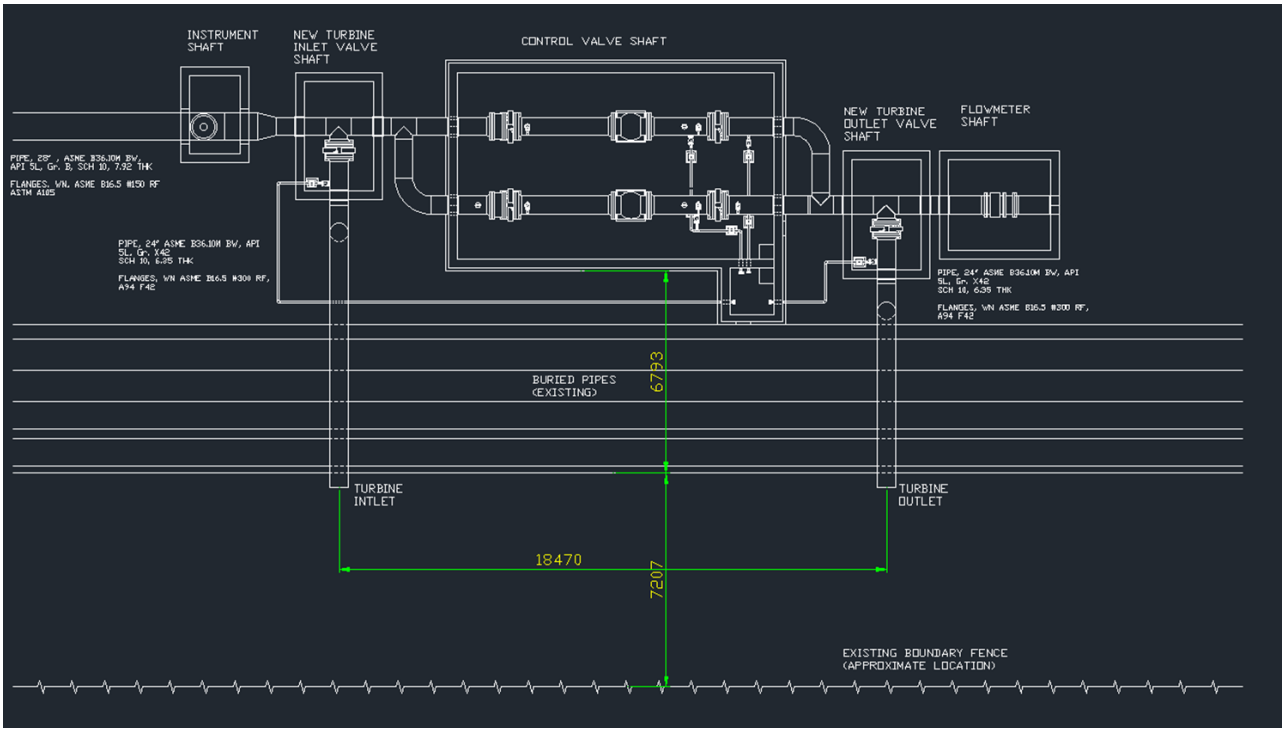


*Figure 2.4: Design of CVS and new turbine allocation*

In terms of transients, the turbine behavior can be described as that of a valve, with abnormal behavior in the event of a change in speed. In the case of a Francis turbine disconnecting from the grid, the turbine starts to overspeed rejecting water i.e., the overspeed determines centrifugal forces that reduce the flow rate. This behavior is very similar to that of a closing valve. Moreover, overspeed and the consequent variation of the flow rate (and so the head) depend on the specific speed.

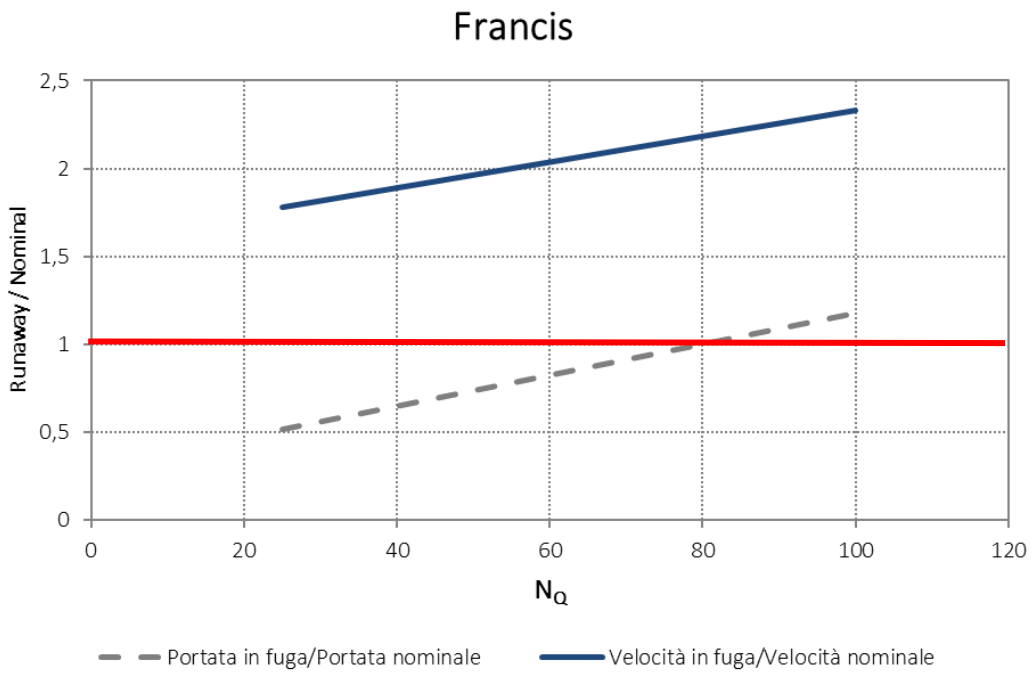


*Figure 2.5: Graph representation of the characteristic number respect to the rate between runaway and nominal speed*

$$N_Q = N \cdot \frac{\sqrt{Q}}{H^{0.75}}$$

So, in our case:

$$N_Q = 1200 \cdot \frac{\sqrt{1.157}}{149.5^{0.75}} \approx 30$$

$N_Q$ is the number of revolutions at which a turbine geometrically similar to the given one must rotate, having a reference length equal to 1 meter and operating with a useful drop of 1 meter, so that the fluid dynamic similarity is respected.

Each type of turbine is characterized by a runaway velocity, which is the maximum speed that it can theoretically reach in the event of load disconnection (due to the opening of the parallel switch or due to an excitation fault) at a time when the hydroelectric unit is working at maximum load.

Francis turbines are made for medium heads and flow rates. Their field of application lies between that of Pelton and Kaplan. The characteristic $N_Q$ numbers cover range from about 20-25 up to 100. For fast Francis, there will be an increase in turbine flow during the overspeed, i.e., when the machine is disconnected, it tends to bring more water into it. This means that the risk of overpressure in the pipeline is limited. On the other hand, the opposite is the case for slow Francis: the leak leads to a very high flow rate, which leads to large overpressures in the pipeline. If we then consider that the slow Francis has a field of application with a medium-high head, it is immediately clear how often it is necessary to provide a safety system against the overpressures of the pipeline. These systems can be synchronous exhausts, spindle valves, flywheels, and must be chosen from time to time to better adhere to the situation under consideration.

## 2.3 The layout

As said previously, the present study analyzes a specific branch of a much wider water distribution system. Upstream, the elevation of the high point reservoir is about 2330 MASL. The elevation of the tap off point from the main line is 2211 MASL. A stainless-

steel penstock, with a length of 4550 meters, links the tap off to the inlet of the turbine. The elevation of the downstream reservoir is 2171 meters.

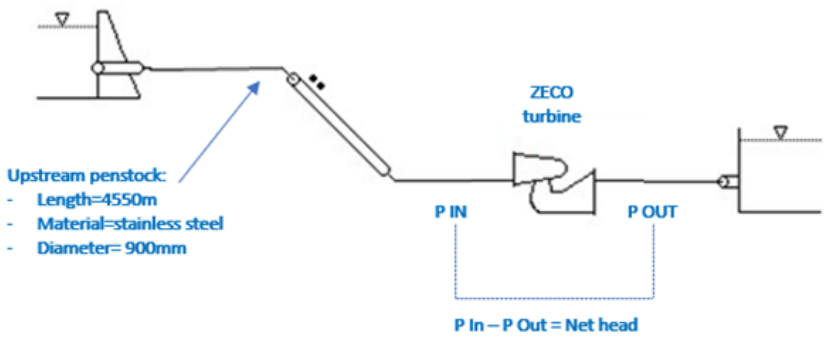


*Figure 2.6: Schematic layout of the system*

Thanks to the data descripted above, a simple yet effective order has been followed. As a matter of fact, in a general case, having:

- Layout and geometry of the penstock
- System operating data
- Inertia of rotating parts
- Sizing of the turbine
- Other data from hydraulic system

It can be simulated:

- Start-up
- Refusal and insertion of the load
- Emergency shut down

To calculate:

- Maximum/minimum pressure
- Overspeed
- Risks of separations of liquid column and cavitation
- Maximum torque
- System stability

The possibility for modelling and simulating hydropower systems as accurately as possible take an important role in order to develop a control structure and to make efficient analysis tools for testing a designed turbine for stability and performance in different operating regimes.

From the following chapters, in fact, having acquired the nominal design conditions, we will focus on the simulations of the plant, with the aim of obtaining those fundamental parameters crucial in the preliminary study phase.

# Chapter 3: The conceptual model in OpenHPL library

OpenHPL is an open-source hydropower library that consists of hydropower unit models and is encoded in Modelica. Modelica is a multi-domain as well as a component-oriented modelling language that is suitable for complex system modelling. In order to develop the library, OpenModelica has been used. OpenModelica is an open-source Modelica-based modeling and simulation environment intended for industrial and academic usage. The goal with the OpenModelica effort is to create a comprehensive Open Source Modelica modeling, compilation and simulation environment based on free software distributed in binary and source code form for research, teaching, and industrial usage. OpenHPL, provides the capability for the modelling of hydropower systems of different complexity.

## 3.1 The elements and governing equations

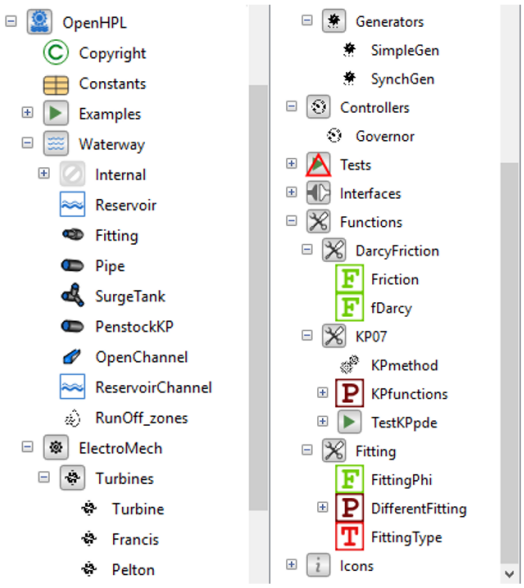


*Figure 3.1: OpenModelica hydropower library*

- the *Constants* element is a record's model that determines the common parameters for the library;
- The *Waterway* class consists of various unit models for the waterway of the hydropower system, such as reservoirs, conduits, surge tank, pipe fittings, etc.;
- The *ElectroMech* class provides the electro-mechanical components of the hydropower system and consists of two main sub-classes: Turbines with various turbine unit models and Generators with models for a synchronize generator;
- the Controllers class holds a simple model for a governor of the hydropower system.

### 3.1.1 Waterway: the reservoir

The water level in the reservoir *Hr* is a key quantity. Similarly, to the water tank, a reservoir model can be described by mass and momentum balances as following:

$$H_r \frac{d\dot{m}_r}{dt} = \frac{\rho}{A_r}\dot{V_r}^2 + A_r(p_{atm} - p_r) + \rho g H_r A_r - F_{f,r}$$

$$\frac{dm_r}{dt} = \dot{m}_r$$

Here, $\dot{m}_r$ is the reservoir mass flow rate that can be found from the reservoir volumetric flow rate $\dot{V}_r$. $A_r$ is a square area of the reservoir. $p_{atm}$ and $p_r$ are the atmospheric and the reservoir outlet pressures, respectively. $F_{f,r}$ is a friction term that can be found using Darcy friction factor.

In a simple case, it can be assumed that the reservoir level is constant, the reservoir inlet flow is equal to the outlet flow, and the reservoir area is closed to infinity. Hence the reservoir can be presented just as an equation for pressure in the inlet/outlet of the reservoir:

$$p_r = p_{atm} + \rho g H_r$$

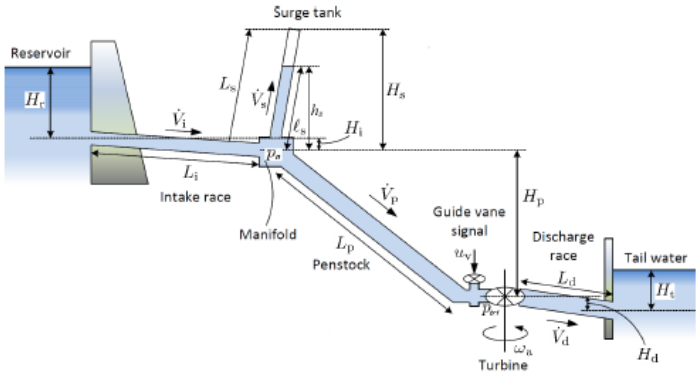


*Figure 3.2: Reservoir structure*

### 3.1.2 Waterway: the penstock

The simple model of the pipe unit Pipe gives possibilities for easy modelling of different conduit: intake race, penstock, tailrace, etc. In these waterway units, there are only small pressure variations due to the small slope angle. That is why the model for these units can be simplified by considering incompressibility of the water and the inelasticity of the walls.

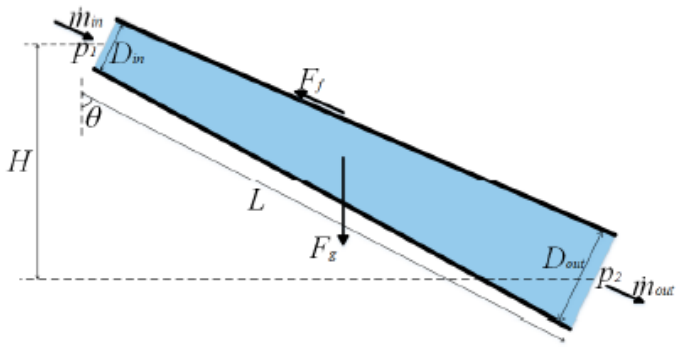


*Figure 3.3: Model for flow through a pipe*

In the case of incompressible water, the mass in the filled pipe is constant, and:

$$\frac{dm_c}{dt} = \dot{m}_{c,in} - \dot{m}_{c,out} = 0$$

Here, the mass of the water in the pipe (conduit) is $m_c = \rho V_c = \rho L_c \overline{A_c}$, where $\rho$ is the water density, $V_c$ the volume of the water in the pipe, $L_c$ the length of the pipe and $\overline{A_c}$ the averaged cross-section area of the pipe that are defined from averaged pipe diameter $\overline{D_c}$. The inlet and outlet mass flow rates are equal with $\dot{m}_{c,in} = \rho \dot{V}_{c,in}$ and $\dot{m}_{c,out} = \rho \dot{V}_{c,out}$ respectively, where $\dot{V}_{c,in} = \dot{V}_{c,out}$ represents the inlet and outlet volumetric flow rates in the pipe.

The momentum balance for the simplified model can be expressed as:

$$\frac{dM_c}{dt} = \dot{M}_{c,in} - \dot{M}_{c,out} + F_{p,c} + F_{g,c} + F_{f,c}$$

Here, the momentum of the water in the pipe is $M_c = m_c v_c$, where $v_c$ is the average water velocity and can be defined as $v_c = \dot{V}_c / \bar{A}_c$. The inlet and outlet momentum flow rates are $\dot{M}_{c,in} = \dot{m}_{c,in} v_{c,in}$ and $\dot{M}_{c,out} = \dot{m}_{c,out} v_{c,out}$ respectively, where $v_{c,in} = \dot{V}_{c,in} / A_{c,in}$ and $v_{c,out} = \dot{V}_{c,out} / A_{c,out}$ are the velocities in the inlet and outlet of the pipe, respectively, and are equal in a case with constant diameter of the pipe. $F_{p,c}$ is the pressure force, due to the difference between the inlet and outlet pressure $p_{c,1}$ and $p_{c,2}$ can be calculated as follow: $F_{p,c} = A_{c,in} p_{c,1} - A_{c,out} p_{c,2}$. There is also gravity force that is defined as $F_{g,c} = m_c g \cos \theta_c$, where $g$ is the gravitational acceleration and $\theta_c$ is the angle of the pipe slope. The last term in the momentum balance is friction force which can be calculated as $F_{f,c} = -\frac{1}{8} L_c f_{D,c} \pi \rho \overline{D}_c v_c |v_c|$ using the Darcy friction factor $F_{D,c}$ for the conduit.

The main defined variable is the volumetric flow rate. In this *Pipe* unit, the flow rate changes simultaneously in the whole pipe (information about the speed of wave propagation is not included here). Water pressures can be shown just in the boundaries

of pipe (inlet and outlet pressure from connectors). This unit uses the *ContactPort* connector model and can be connected to other waterway units.

When the *Pipe* unit is in use, the user can specify the required geometry parameters for this pipe: length $L_c$, height difference $H_c$, inlet and outlet diameters $D_{c,1}$ and $D_{c,2}$, and pipe roughness height $\varepsilon_c$.

### 3.1.3 Electro-Mechanical: the turbine

The turbine unit can be expressed with a simple turbine model based on a look-up table (turbine efficiency vs. guide vane opening). This simple turbine model is described by the following equation, where the mechanical turbine shaft power is defined as:

$$\dot{W}_{tr} = \eta_h \Delta p_{tr} \dot{V}_{tr}$$

Here, $\eta_h$ gives the turbine hydraulic efficiency that is found from a standard turbine lookup table and depends on the turbine control signal, $u_v$. $\Delta p_{tr}$ is the pressure drop through the turbine that is defined as the difference between inlet and outlet turbine pressures, i.e., $\Delta p_{tr} = p_{tr,1} - p_{tr,2}$. The relationship between the turbine volumetric flow rate $\dot{V}_{tr}$ and the pressure drop $\Delta p_{tr}$ is described through a simple valve-like expression as follows:

$$\dot{V}_{tr} = C_v u_v \sqrt{\frac{\Delta p_{tr}}{p^a}}$$

Here, $C_v$ is some guide vane "valve capacity" that can be tuned by using the nominal turbine net head (nominal pressure drop) and the nominal turbine flow rate. $p^a$ is the atmospheric pressure.

Based on the last equations, the simple turbine model is implemented in *OpenHPL* as the *Turbine* element. In this *Turbine* unit, the multi-physic connections are used in order to

stay connected to waterway units as well as to the other electro-mechanical units. Those connections are already implemented in the *TurbineContacts* connectors model that is used in this *Turbine* unit. Then, this unit can be connected to other waterway and electro-mechanical units.

In the *Turbine* unit, the user can specify the required parameters for the simple turbine model: guide vane "valve capacity" $C_v$, the nominal turbine net head (nominal pressure drop) and the nominal turbine flow rate, turbine guide vane nominal opening signal $u_{v,n}$ in per unit value from 0 to 1. The user can also choose either to use the constant turbine efficiency and specify it, or to use the look-up table for the turbine efficiency and also specify this table.

## 3.2 The simulation 1: find the initial conditions

The OpenHPL library integrated in OpenModelica software was used to develop the model in a situation of standard operating closure, therefore it was imposed a closure of the turbine from the grid in 10 seconds.

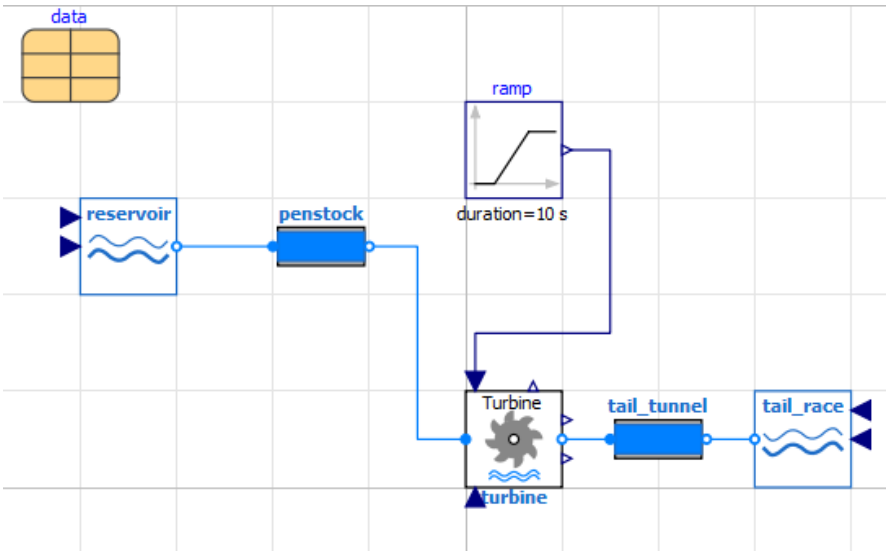


*Figure 3.4: Schematic representation of the system in OM*

### 3.2.1 Data

The input data of the model respect the design water characteristics provided by the Client (temperature of 30 °C and density of 995,65 kg/m$^3$); with these, all the others related water's properties were derived with the support of miniREFPROP software. Gravity constant was changed due to the conditions previously explained. Initial system frequency is set to 60 Hz which is the standard grid frequency in Saudi Arabia.

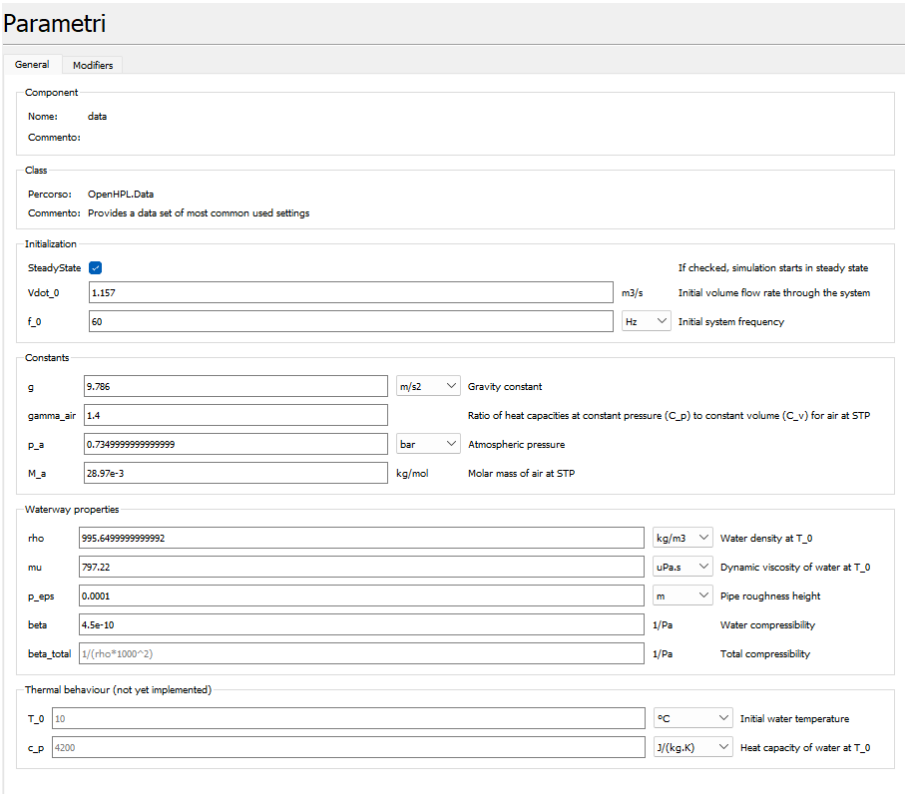


*Figure 3.5: Window "data"*

### 3.2.2 Reservoir

The upstream reservoir has an initial water level above the intake of 10 meters. The geometry of the structure was not specified as is not a requirement for the purposes of the study in question (The data written in grey were left not specifies as default values).

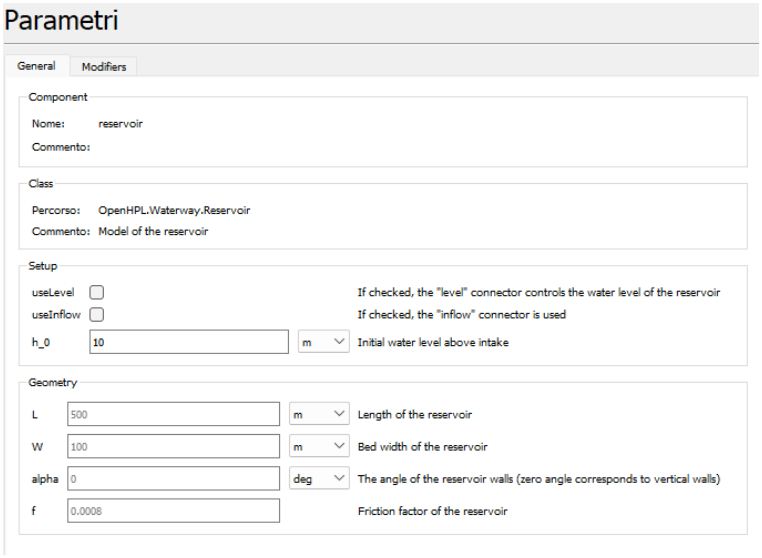


*Figure 3.6: Window "Reservoir"*

### 3.2.3 Penstock

The pipe that links the reservoir directly to the turbine has a height difference from the inlet to the outlet of 149,5 meters. This represents the nominal net head.

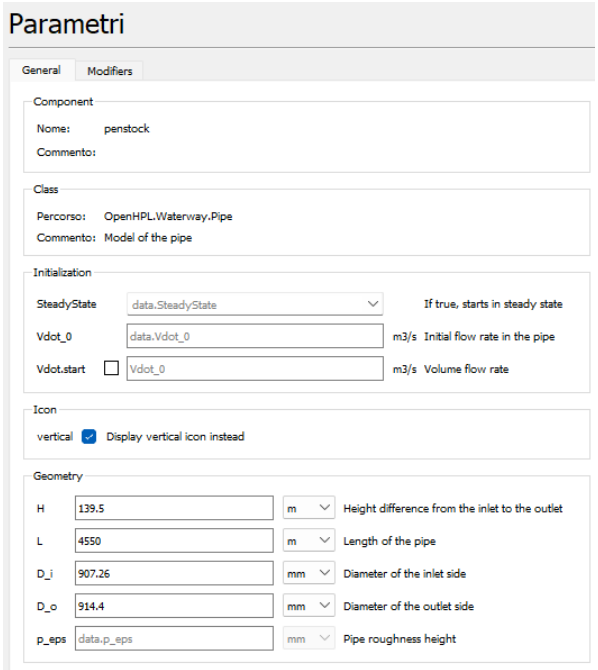


*Figure 3.7: Window "Penstock"*

### 3.2.4 Turbine

The nominal net head and the nominal flow rate together with the nominal turbine velocity are enough to define the turbine profile. In addition, efficiency must be specified: the following look-up table contains the turbine efficiency values for the project. As a matter of fact, we have a table that correlates the opening angle with the efficiency of the Francis. The angle of 21° represents the maximum opening through which the nominal discharge Q can be processed at nominal head H.

| % | Q [m³/s] | H [m] | P [kW] | $\eta_T$ [%] | Pesi | Ap [°] |
|---|---|---|---|---|---|---|
| 100 | 1,160 | 149,5 | 1548,39 | 92,2 | 1 | 21,0 |
| 90 | 1,044 | 149,5 | 1385,22 | 91,6 | 0 | 19,2 |
| 80 | 0,928 | 149,5 | 1218,20 | 90,7 | 0 | 17,5 |
| 70 | 0,812 | 149,5 | 1053,44 | 89,6 | 0 | 15,9 |
| 60 | 0,696 | 149,5 | 882,69 | 87,6 | 0 | 14,3 |
| 50 | 0,580 | 149,5 | 709,78 | 84,5 | 0 | 12,6 |
| 40 | 0,464 | 149,5 | 537,53 | 80 | 0 | 11,0 |

*Table 3.1: Look-up table for the Francis under examination*

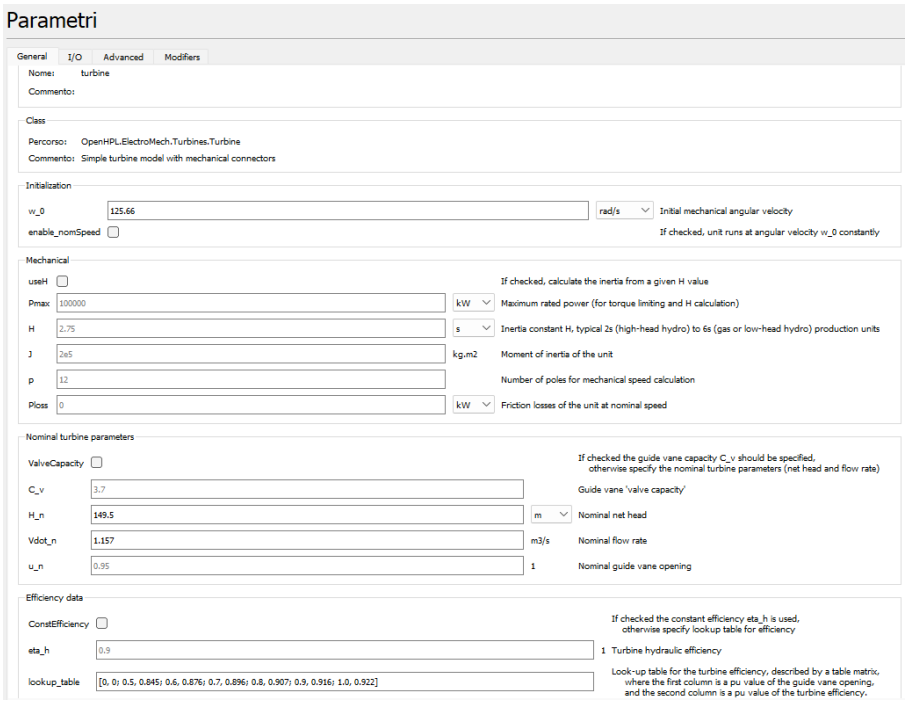


*Figure 3.8: Window "Turbine"*

### 3.2.5 Ramp Signal

The turbine characteristics are simulated during a normal closure condition. After, the power of turbine is near 0 kW. The entire procedure is set to take place in 10 seconds. Considering that the plant is operating at 100% of nominal discharge, the maneuver starts at 10 seconds with a normalized parameter of 1 (offset). After another 10 seconds, the distributor is completely closed; that means that afterward the nominal discharge is 0,1% (it cannot be 0% for safety reasons). The height represents the difference between the nominal discharge before and after the maneuver, in this case 0.9.

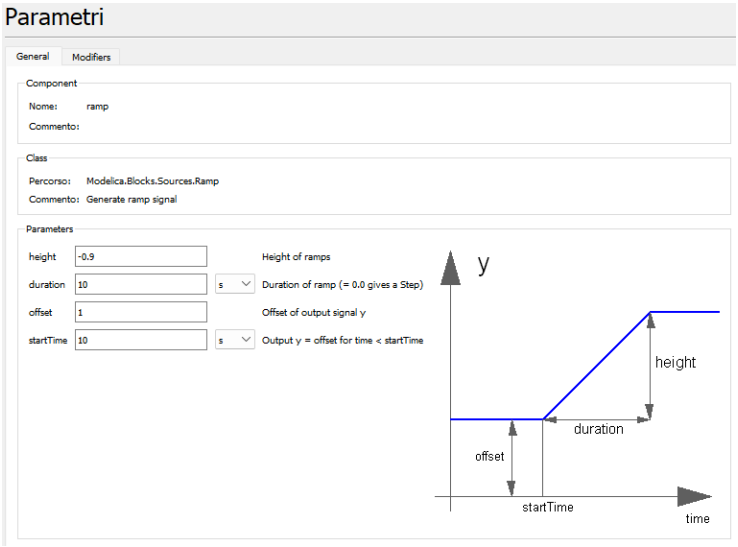


*Figure 3.9: Window "Ramp Signal"*

### 3.2.6 Tail tunnel

In OpenModelica, a tail tunnel must be set up to close the hydraulic path. In this case a length of 1 meter has been used in order to link the turbine to the downstream reservoir.

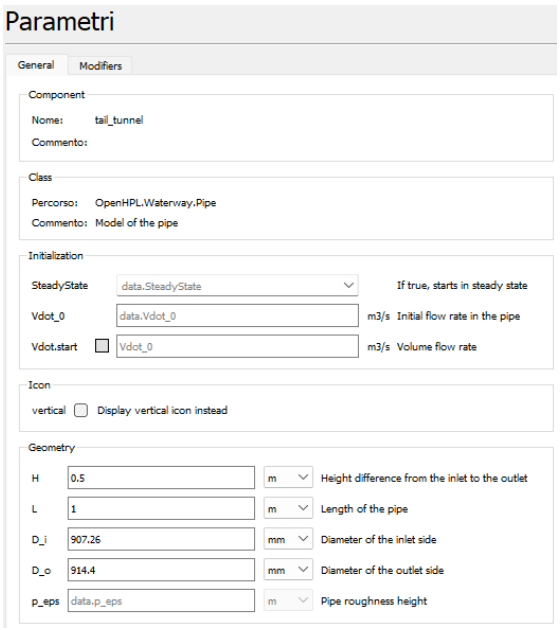


*Figure 3.10: Window "Tail Tunnel"*

### 3.2.7 Tail Race

The reservoir downstream of the turbine has a water level above intake of 10 meters.

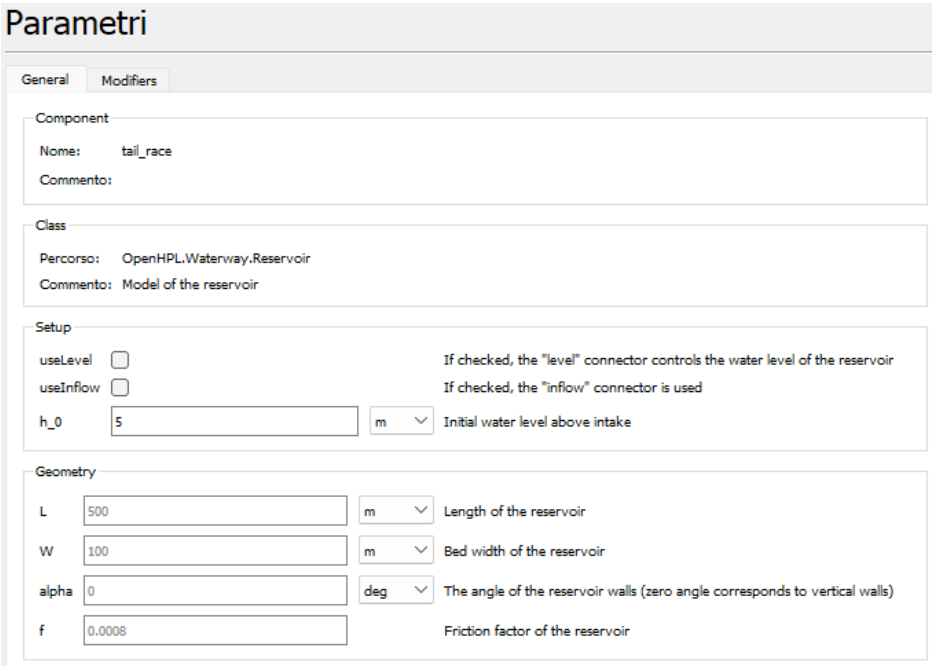


*Figure 3.11: Window "Tail race"*

### 3.2.8 Simulation Set Up

The case study considers a closure maneuver at 10 seconds. Therefore, a simulation's interval between 0 seconds and 80 seconds is considered sufficient to appreciate the dynamic's changes in the system.

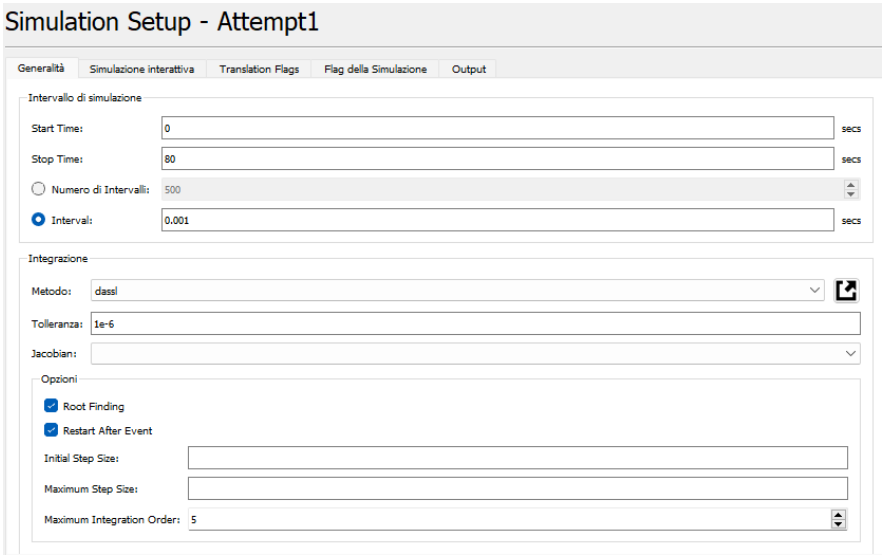


*Figure 3.12: Window "Set Up"*

### 3.2.9 Results of the simulation 1

The maneuver starts at 10 seconds. From a nominal discharge of 1, within 10 seconds, the maneuver occurs, dropping the discharge down to 0.1.

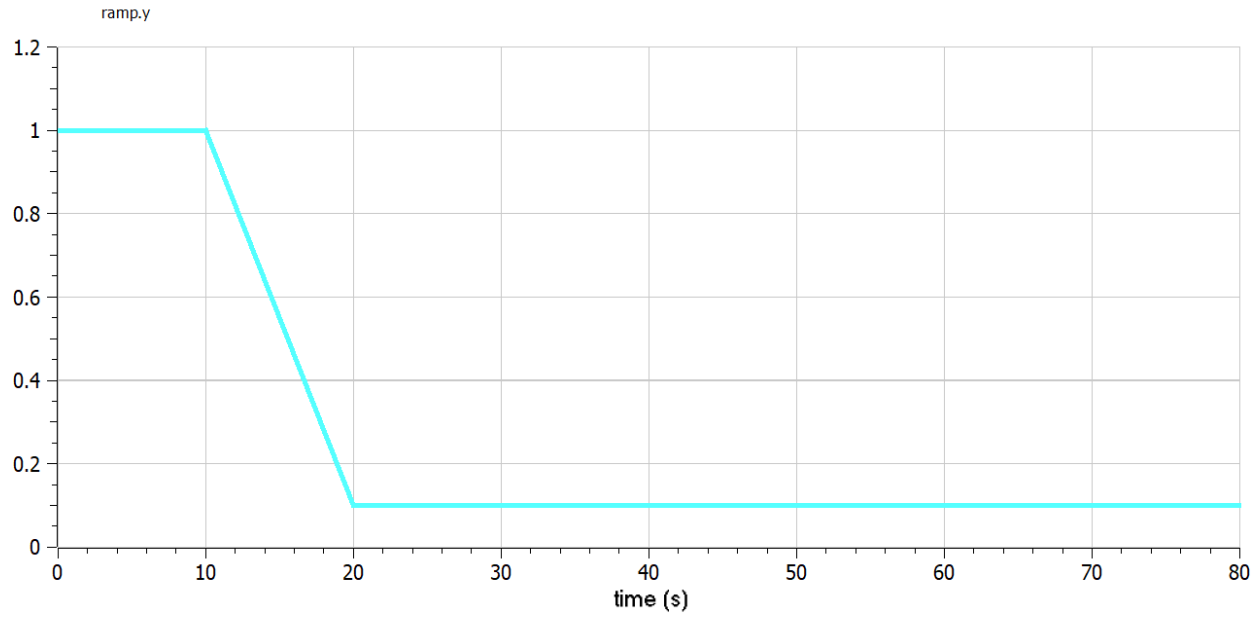


*Figure 3.13: Ramp signal in function of the time*

For what concerns the power changes in the turbine, from 10 seconds onward it is possible to see the power increasing up above 1.5 MW and then suddenly drops near to zero within 8 seconds. With reference to the following graph, it can be seen that in the very first moment of the closing maneuver, an increase of head leads to an increase of power. This apparently paradoxical manner is due to the link that still exists between the two parameters in the first seconds: $P = \eta \rho g Q H$. However, after a short time, the gradual closure of the distributor and, consequently, the decrease in flow rate 'wins' against the increasing head, so the power finally starts to decrease until it reaches a value close to zero at 20 seconds when the distributor is completely closed.

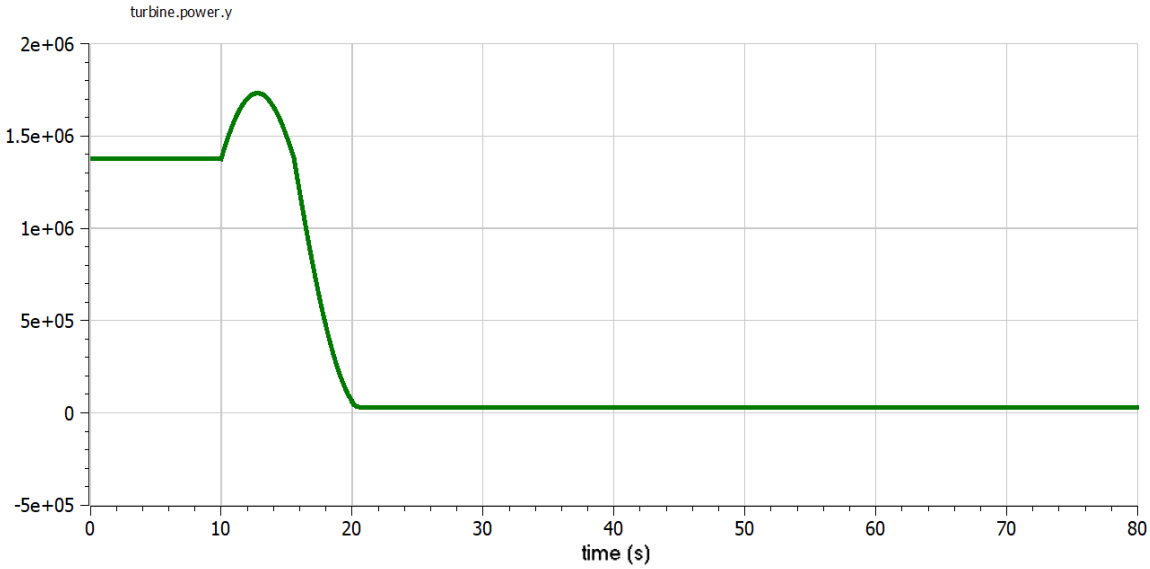


*Figure 3.14: Turbine power in function of the time*

In terms of turbine pressure, as expected, the closing maneuver causes a significant increase. This progress starts in a fast way, but it slows down as long as the closure maneuver progresses. At the end, pressure abruptly drops near the nominal value of the pressure.

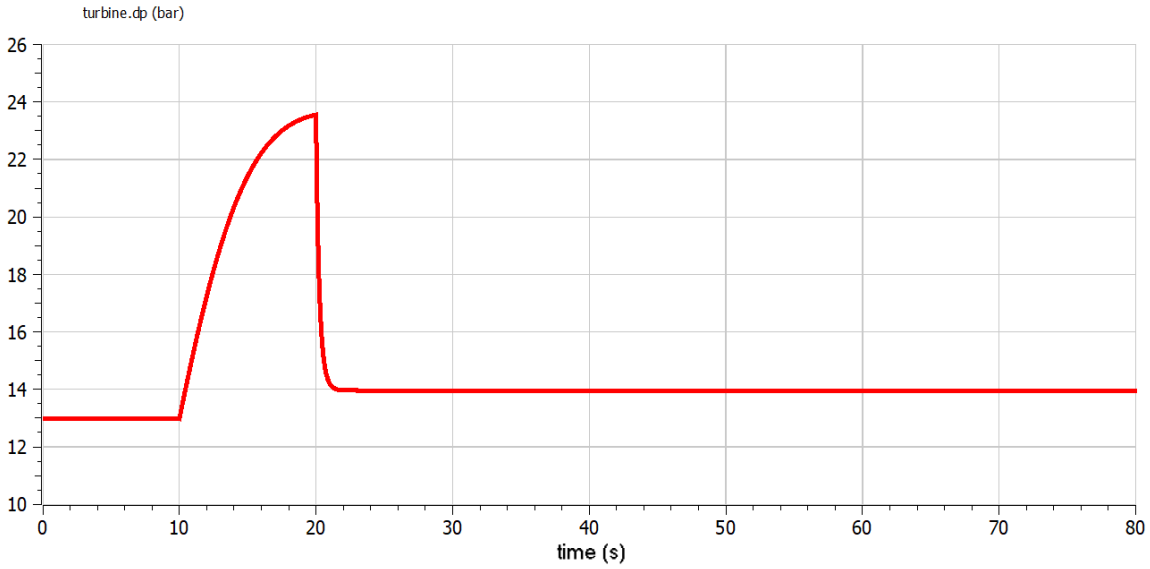


*Figure 3.15: Turbine pressure in function of the time*

For what concerns the flow rate, clearly in the first seconds the discharge is compatible with the nominal one. During the maneuver, a linear behavior down to 0.11924 $m^3/s$ can be seen.

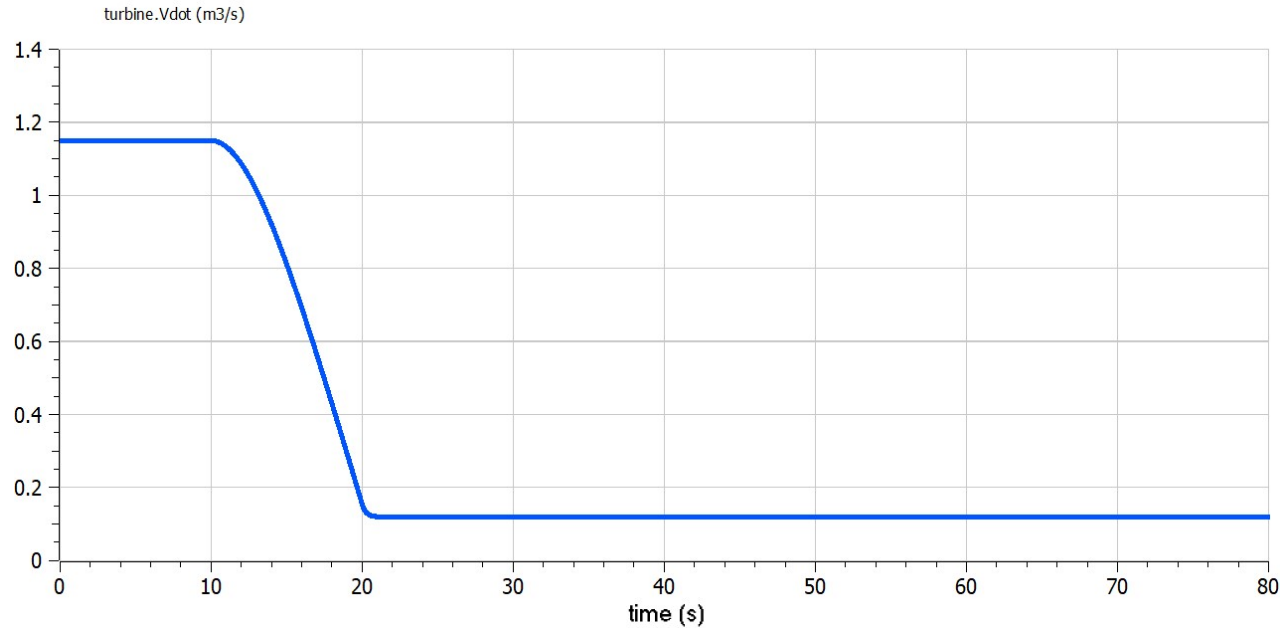


*Figure 3.16: Turbine flow rate in function of the time*

Notice that, for what concerns the power absorbed by the system, the relative graph shows a power smaller than the nominal one. It will be necessary to play with the losses to have a better estimation of the turbine.

Moreover, notice that in none of the graph previously described, after the closure there is no oscillations of the perturbations are observed. This could underline the lack of sensitivity of OpenModelica in detecting hydraulic transients, at least for this type of systems that do not include a surge tank placed upstream of the turbine.

## 3.3 The simulation 2: optimization of the model

As previously said, the first simulation shows a power absorbed by the turbine smaller the nominal one. It is thus necessary to play with the losses. Remembering that for OpenModelica, the simple turbine model is described by the following equation, where the mechanical turbine shaft power is defined as:

$$\dot{W}_{tr} = \eta_h \Delta p_{tr} \dot{V_{tr}}$$

The relationship between the turbine volumetric flow rate $\dot{V_{tr}}$ and the pressure drop $\Delta p_{tr}$ is described through a simple valve-like expression as follows:

$$\dot{V}_{tr} = C_v u_v \sqrt{\frac{\Delta p_{tr}}{p^a}}$$

Here, $C_v$ is some guide vane "valve capacity" that can be tuned by using the nominal turbine net head (nominal pressure drop) and the nominal turbine flow rate. $p^a$ is the atmospheric pressure.

Therefore, in this case, differently from the simulation number one where just head and flow rate were fixed, it has been decided to change the values of the $C_v$ in order to have a better representation of the system. Each parameter has been left as is. After several attempt, a value of $C_v$ equal to 0.26 has given a good result.

### 3.3.1 Results of the simulation 2

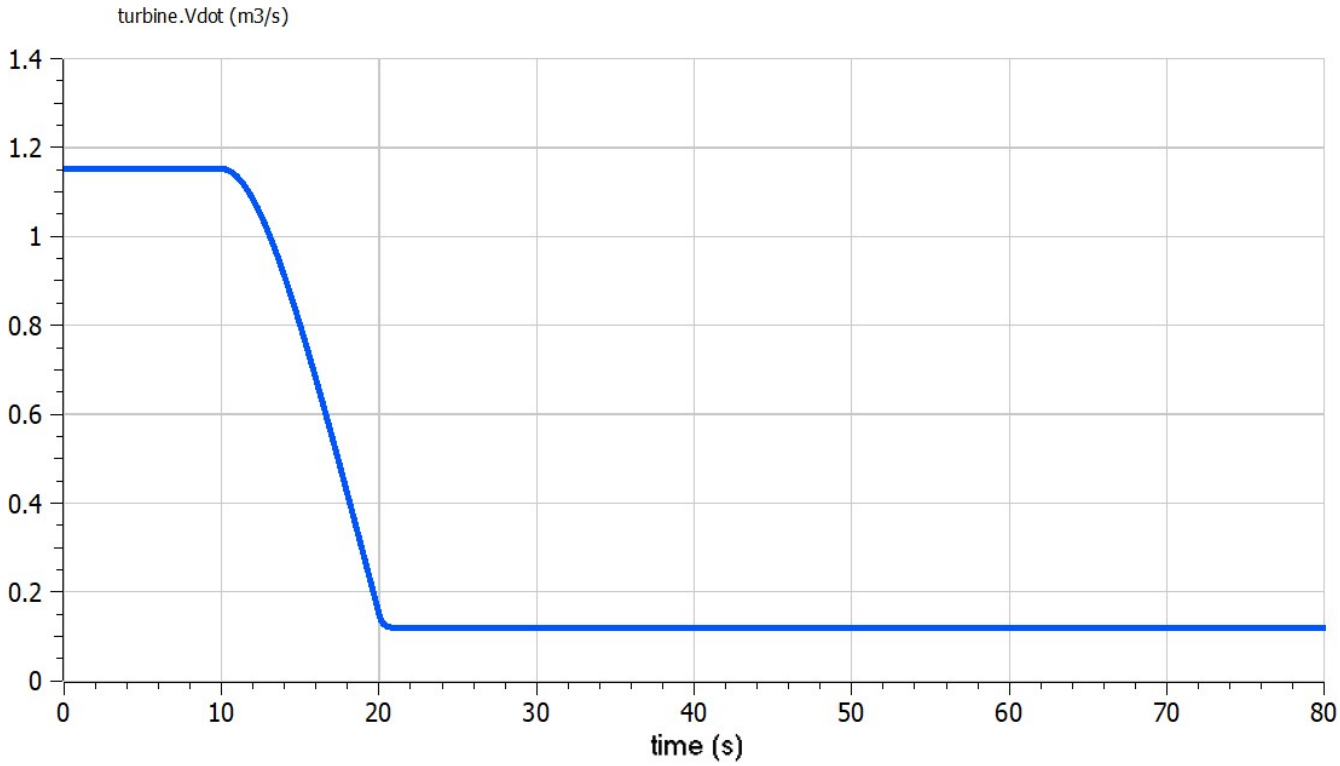


*Figure 3.17: Turbine flow rate in function of the time*

Clearly, a good representation of the flow rate still exists, even in this simulation. In fact, the initial flow rate is quite similar to the nominal one (1,157 $m^3/s$) and it follows a linear decrease until almost reaching the value 0 when the distributor is closed.

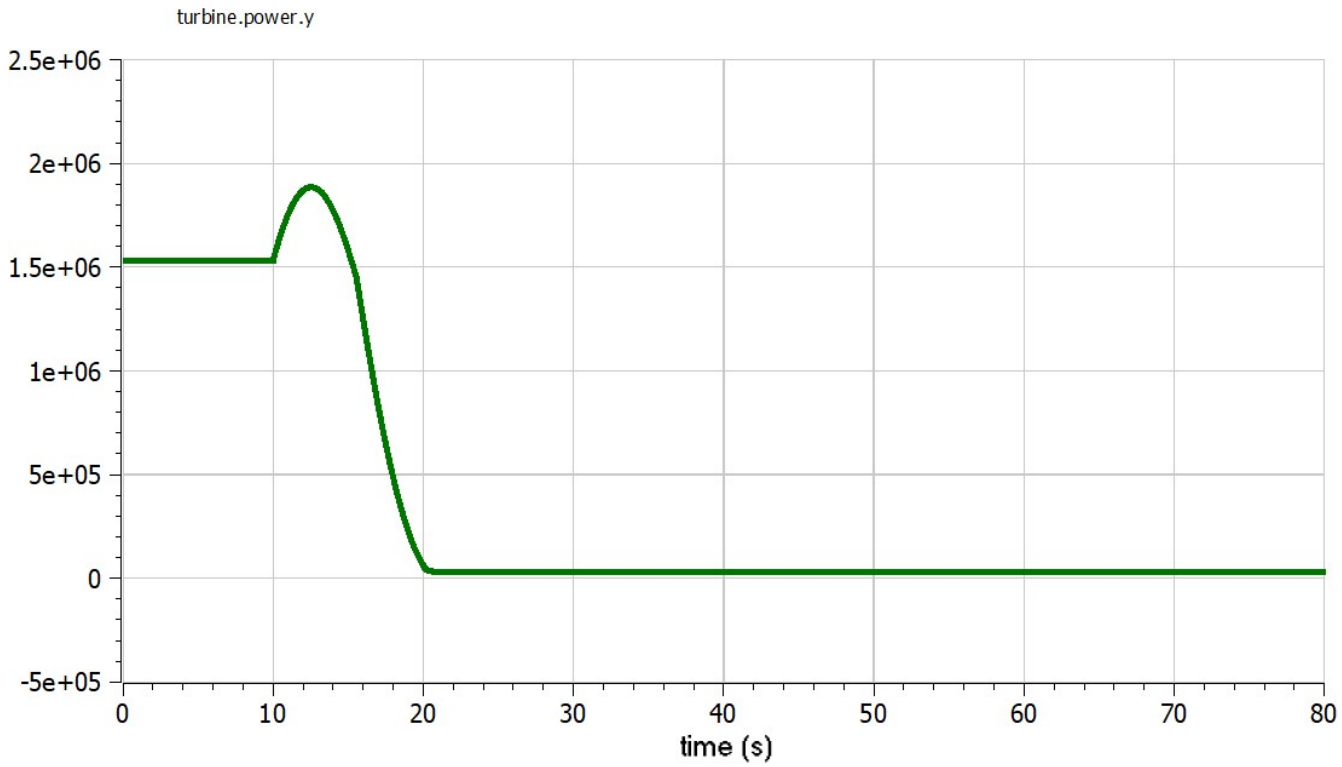


*Figure 3.18: Turbine power in function of the time*

Thanks to this simulation, a better representation of the power can be seen: the initial power absorbed by the turbine is almost equal to the nominal one (1548 kW). This validates the goodness of this simulation respect to the previous one.

Probably the differences in the results have to be attributed to the fact that OpenModelica works with a bidimensional parameterization; it takes into account flow rate and efficiency but it does not consider the head as well.

In the next chapter, the results of the model dynamics will be compared to the ones find in the commercial software SIMSEN. It will be explained how much these comparisons will show good fitting.

# Chapter 4: The conceptual model in SIMSEN

SIMSEN software enables to simulate power systems dynamics, with a strong emphasis on the hydropower station dynamics. Indeed, SIMSEN takes into account complex hydraulic machinery and waterways, as well as electrical machines, power electronics and the control systems. This software is an advanced numerical tool, widely used by the industry and academia for simulating the dynamics of power systems, with a strong capability to model entire hydropower plants; waterways and systems models take into account distributed head losses, geometry, elasticity and wave speed. The hydraulic machine model takes into account the 4-quadrants performance hill chart to simulate their dynamic behavior. These models are formulated using an electrical analogy in order to facilitate the automatic equation generation of the whole system (using Kirchhoff voltage and current laws).

## 4.1 The element and the governing equations

The Courant-Friedrichs-Lewy (CFL) condition applies to ensure stability of numerical resolution of propagation phenomena such as water hammer problems. If convective terms are neglected, this condition can be expressed as follows:

$$a \cdot dt \leq dx$$

Where $dt$ is the integration time step, $dx = L/N_b$ is the length of the elements modeling the pipe, and $a$ is the wave speed. The CFL condition defines the minimum integration time step to ensure that numerical integration is achieved with integration time step smaller than the time for hydraulic quantities (pressure or discharge) to propagate through an element of length $dx$.

To ensure integration stability, it has been identified, that for systems that are physically unstable, it is also important to exchange the hydraulic quantities between two pipes strictly at the end of the integration time step dt. To do so, it is necessary to use appropriate and uniform piping system discretization and adapted wave speed.

$$Characteristic\ lines: \frac{dx}{dt} = \pm a$$

To ensure stability and accuracy of the numerical integration process, it is required that the hydraulic quantities are transferred between pipes at the same time $dt1 = dt2 = dt$. As the ratio between pipe length and wave speed never gives the same propagation time $dt1$ or $dt2$, the wave speed in the pipes must be adapted from a to $a'$. The wave speed is adapted with respect to a time basis $dT$ so that the number of elements $Nb$ modeling a pipe becomes a natural number:

$$Nb = \frac{L}{a' \cdot dT}$$

Wave speed is preferred for adaptation as length of pipes are well defined while wave speed features uncertainties of about +/- 10% due to influence of piping surrounding, pipe fixing, air content, fluid temperature, etc. For water hammer problem, $dT = 0.01s$ is a standard value.

### 4.1.1 Waterway: the reservoir

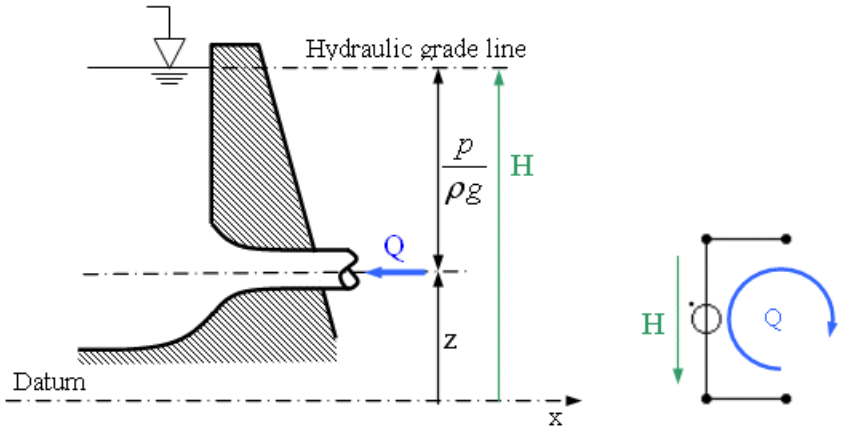


*Figure 4.1: Schematic representation of the reservoir and electrical analogy*

The hydraulic head Hi in a section is given by:

$$H_i = z_i + \frac{p_i}{\rho \cdot g} + \frac{Q_i^2}{2 \cdot g \cdot A_i^2}$$

Where $z_i$ is the elevation, $A_i$ is the cross-section area and $p_i$ is the pressure at the position $i$.

The reservoir model is based on an electrical analogy, which allows modeling a hydraulic component as a set of discrete elements such as RLC elements. The reservoir corresponds to a voltage source.

### 4.1.2 Waterway: the pipe

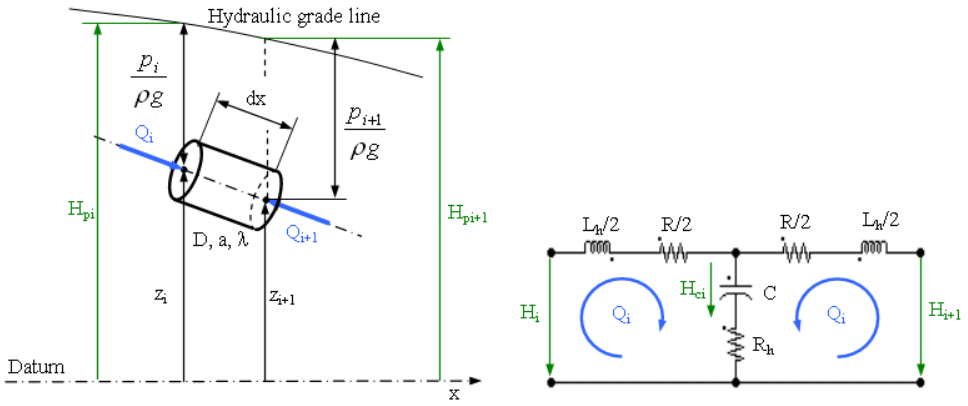


*Figure 4.2: Schematic representation of the pipe and its electrical analogy*

A circular cross-section pipe is characterized by a constant diameter $D$, a wave speed $a$, a length $L$ and a local loss coefficient $\lambda$. The discharge $Q$ is described as entrant in both side of the pipe.

The piezometric head $H_p$ is defined by:

$$H_{pi} = z_i + \frac{p_i}{\rho g}$$

Where $p_i$ is the pressure at the position i. The hydraulic head $H_i$ in a section is given by:

$$H_i = z_i + \frac{p_i}{\rho \cdot g} + \frac{Q_i^2}{2 \cdot g \cdot A_i^2}$$

Where $A_i$ is the cross-section area at the position $i$.

The pipe model is based on an electrical analogy which allows modeling a hydraulic component as a set of discrete elements such as RLC elements. Then the pipe is divided in $Nb$ parts of a length $dx$.

The length is defined by:

$$dx = \frac{L}{Nb}$$

All the RLC elements of the model are related to one part of the dynamic behaviour of the pipe:

- the resistance corresponds to the head losses in the pipe
- the inductance corresponds to the inertia water in the pipe
- the capacitance corresponds to the discharge storage by the wall deformation and the fluid compressibility

According to the continuity and momentum equations the RLC terms are given by:

$$R = \frac{dx\lambda|Q|}{2gDA^2} \qquad L_h = \frac{dx\xi}{gA} \qquad C = \frac{dxgA}{a^2}$$

The evaluation of the wave speed leads in the knowledge of the fluid bulk modulus and density, and the conduit elasticity $\Delta A/(A \cdot \Delta p)$. Assuming a constant Young's modulus of the pipe wall $Ec$ and a constant wall thickness $e$, the wave speed is given by:

$$a = \sqrt{\frac{1}{\rho\left(\frac{1}{E_{fluid}} + \frac{D}{e \cdot E_e}\right)}}$$

### 4.1.3 Electromechanical: the turbine

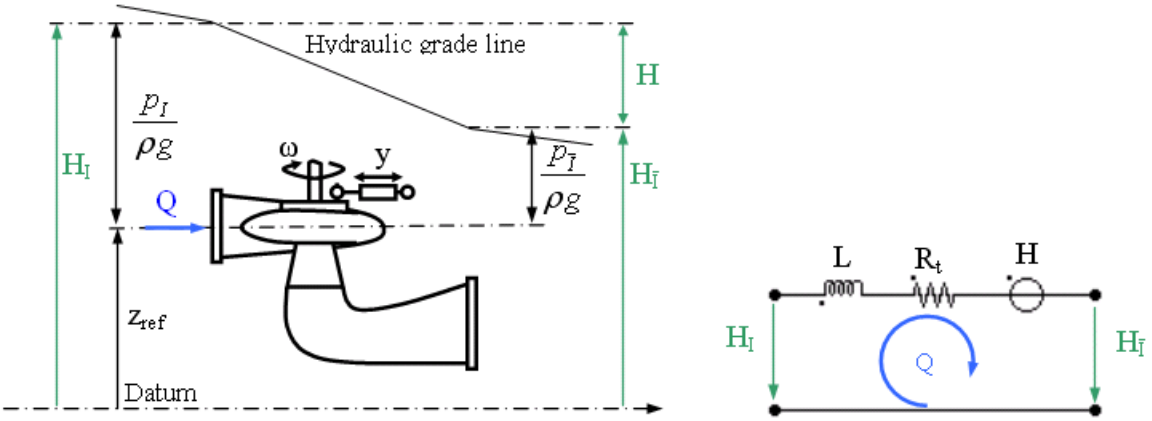


*Figure 4.3: Characteristic representation of the turbine and its electrical analogy*

The piezometric head $H_p$ is defined by:

$$H_{pi} = z_i + \frac{p_i}{\rho g}$$

Where $p_i$ is the pressure at the position i. The hydraulic head $H_i$ in a section is given by:

$$H_i = z_i + \frac{p_i}{\rho \cdot g} + \frac{Q_i^2}{2 \cdot g \cdot A_i^2}$$

Where $A_i$ is the cross-section area at the position $i$.

The turbine model is based on an electrical analogy, which allows modeling a hydraulic component as a set of discrete elements such as RLC elements.

The LRH elements of the model are related to one part of the dynamic behavior of the turbine:

- the pressure source corresponds to the energy transfer given by the characteristic curves
- the resistance corresponds to an additional head loss
- the inductance corresponds to water inertia effects

The inductance term depends on the geometry of the turbine, given by:

$$L = \int_{I}^{\bar{I}} \frac{1}{gA(x)} dx = \frac{J_h}{g}$$

Assuming that the transition between two operating points of a turbine corresponds to a succession of steady state operating points, the transient behavior of this hydraulic machine can be modelled using characteristic curves.

## 4.2 The initialization 1: find the initial conditions

In order to compare the output of the two software, the same data used for the simulation in OpenModelica have been inserted into the SIMSEN environment.

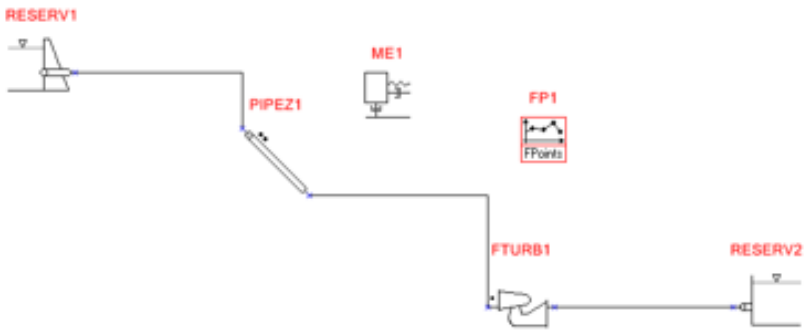


*Figure 4.4: The system in SIMSEN*

### 4.2.1 Reservoir

SIMSEN environment works with difference s of head, in particular the gross head, which for this specific case is equal to H=160 meters.

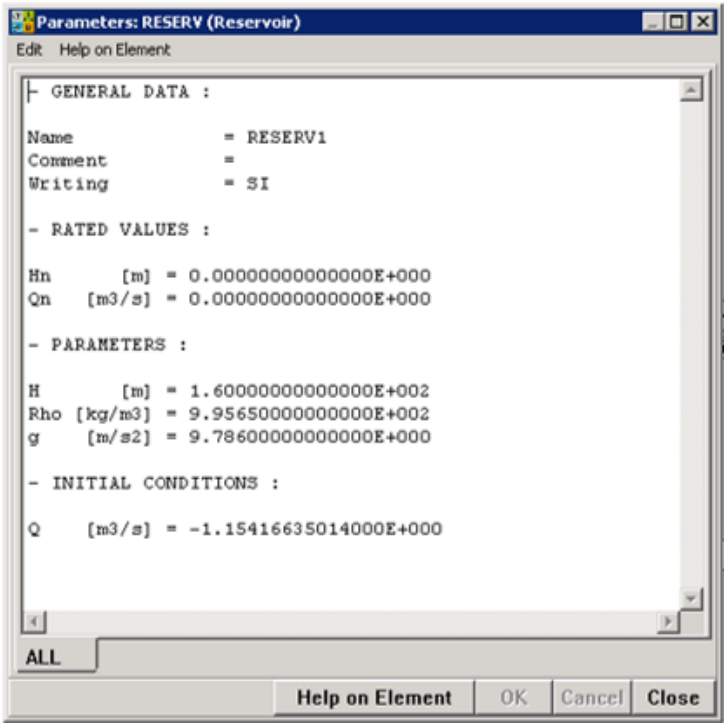


*Figure 4.5: Window "Reservoir"*

### 4.2.2 Pipe

A particular attention needs to be put in the integration interval. From experience it has been seen that a standard value for which the calculation arrives to convergence is Nb=10. Moreover, in this environment, a crucial parameter that must be specified is the celerity $a$.

- Young Module Water: $E_{water} = 1.96 \cdot 10^{9} \ N \cdot m^{-2}$
- Young Module Stainless Steel: $E_{ss} = 2.07 \cdot 10^{11} \ N \cdot m^{-2}$
- Water density: $\rho = 995.65 \ kg \cdot m^{-3}$
- Pipe diameter: $D = 0.9 \ m$

- Pipe thickness: $s = 0.00714\ \ m$

$$a = \frac{\sqrt{\frac{E_{water}}{\rho}}}{\sqrt{1 + \frac{D}{s} \cdot \frac{E_{water}}{E_{ss}}}} = \frac{\sqrt{\frac{1.96 \cdot 10^9}{995.65}}}{\sqrt{1 + \frac{0.9}{0.00714} \cdot \frac{1.96 \cdot 10^9}{2.07 \cdot 10^{11}}}} = 947.335\ m/s$$

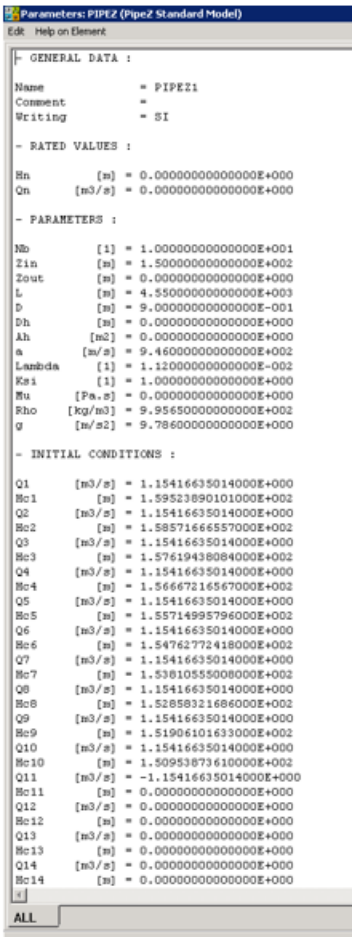


*Figure 4.6: Window "Pipe"*

### 4.2.3 Turbine

To simulate turbines, turbine characteristic curves are required: rotating elements are additional localized resistances whose characteristics change with the opening and with the speed and whose output is a function of efficiency. SIMSEN works in non-dimensional terms on the curves Q11-N11-T11. The characteristic curves affect, in addition to the speed and the power, the overpressure in the penstock as well.

To find out the overspeed curves, SIMSEN needs hill charts in N11-Q11-T11:

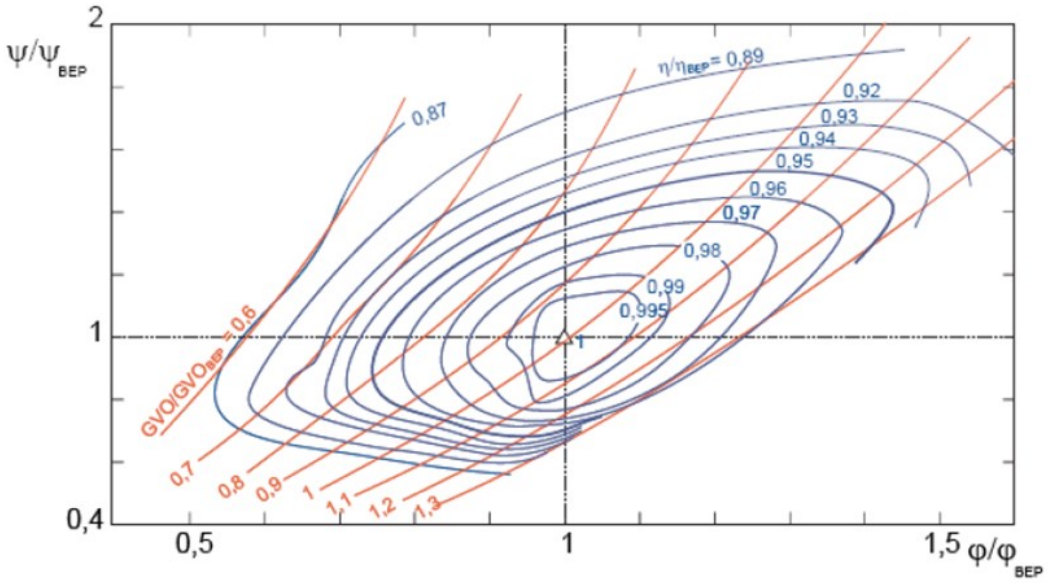


*Figure 4.7: SIMSEN hill charts for Francis turbine*

$$N_{11} = \frac{N \cdot D_{ref}}{\sqrt{H}}$$

$$Q_{11} = \frac{Q}{D_{ref}^2 \cdot \sqrt{H}}$$

$$T_{11} = \frac{T}{D_{ref}^3 \cdot H}$$

Good practice when analyzing transient phenomena with hydropower turbines is to display results in terms of the percentage (pu) with respect of the nominal values can be seen better. $y$ represents the turbine distributor opening that, for now, is considered equal to zero. $Dref$ represents the diameter at the exit of the impeller: for the chosen turbine $Dref$ is equal to 0.4873 meters. From the experience, $Lequ$ is more or less 5 or 10 times higher than $Dref$. These are the initial conditions applied to the system.

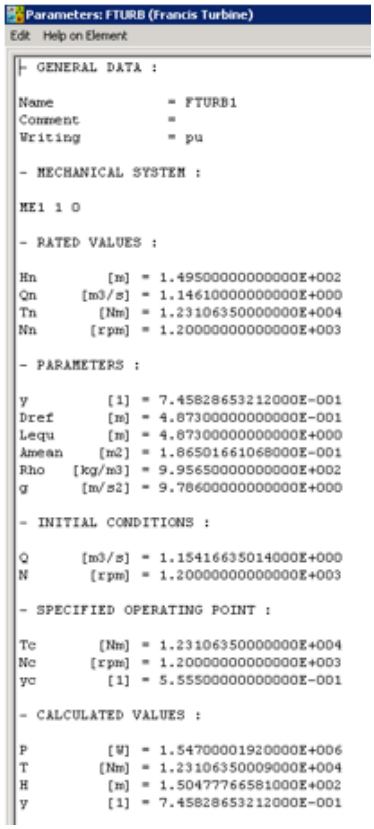


*Figure 4.8: Window "Turbine"*

### 4.2.4 Results of the initialization 1

The purpose of the first simulation is to initialize the system i.e., find the exact opening that allows the nominal flow rate to pass through the turbine under the nominal head condition. From the graph, the system stabilizes after 80 seconds, with pressure and flow rate that converge to the nominal ones. Differently, the head (red line) cannot be exactly

initialized to correspond to the nominal one. In other terms, to get a better initialization in term of head, we need to run a second simulation by playing with pipe distributed losses, $\lambda$. Moreover, the optimal aperture $y$, for which it was given an initial value of zero, results to be slightly under 75%; in the second simulation, setting this value will be necessary to have a better representation of the system.

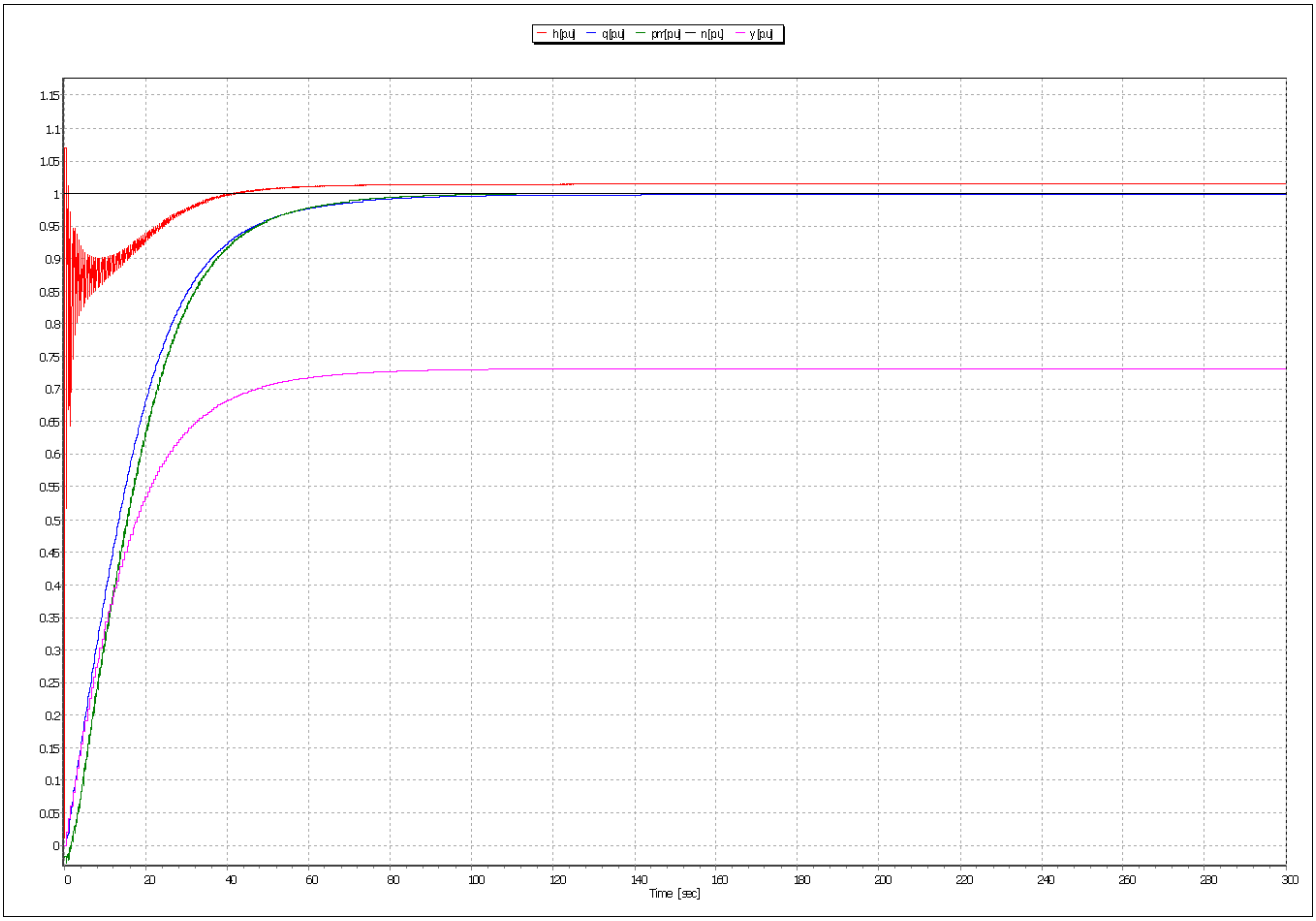


*Figure 4.9: Graph representation of parameters in the first initialization*

## 4.3 The initialization 2: optimization of the model

From the graph of Figure 4.9, it has been noted that the head $h$ is a little bit higher than the unit: there is the need to play with the losses to close that gap. It has been chosen to increase the value of $\lambda$ up to $0.012$; with higher losses a better estimation can be

obtained. For the second simulation, adding the peculiarity of maneuver is fundamental: the value of $y$ (violet line) is the one obtained from the graph: 74,58% of aperture is the value that optimize the triangular speed of the turbine.

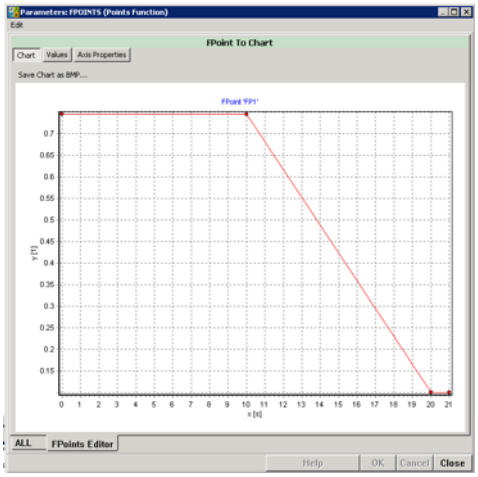


*Figure 4.10: Ramp control of the distributor*

Appling "Mechanical Mass" allows to add inertia to the system. Since in OpenModelica this function is not available, to make the simulation as faithful as possible, an inertia $J$ equal to $1 \cdot 10^{12}$ has been applied, a number considered infinite.

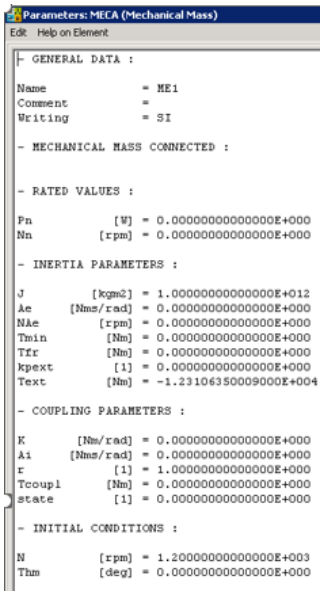


*Figure 4.11: Window "Mechanical Mass"*

### 4.3.1 Results of the initialization 2

After the improvements made to the system, clearly a convergence of the parameters to the nominal ones is obtained. Since such a good convergence has been found, the values obtained can be used for simulating the maneuver and study the perturbations in the system.

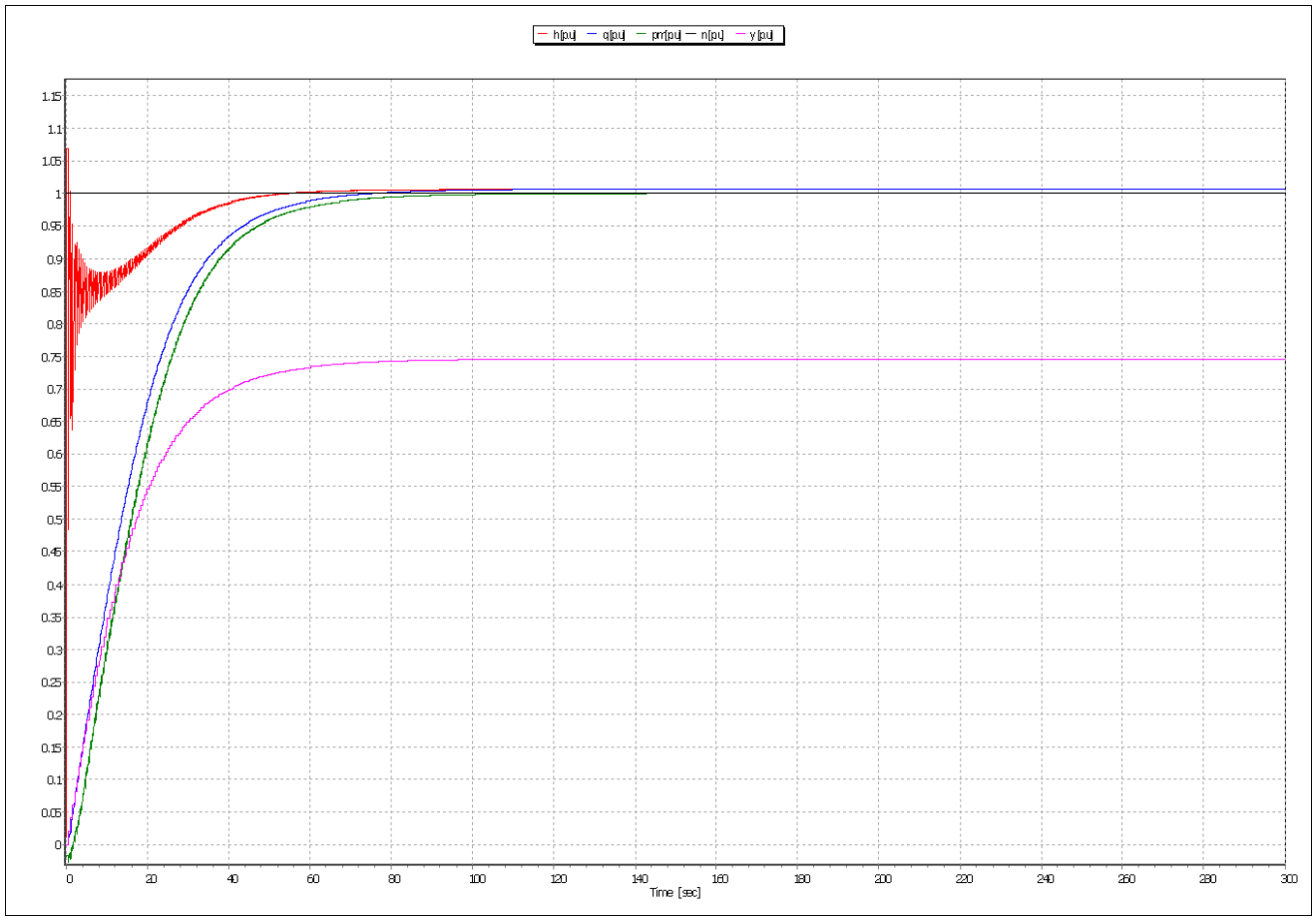


*Figure 4.12: Graph representation of parameters in the second initialization*

## 4.4 SIMSEN final simulation

From the results of the simulation, some observations can be done (Figure 4.13):

- As the distributor closes, the head (red line) increases its value till reaching almost twice its nominal value. At 20 seconds, it starts to decrease quickly down to half of the nominal value. This oscillation continues over and over again as the tip values decrease over time
- The flow rate (blue line) starts from the nominal value. Obviously, the maneuvers cause a fast decrease in the discharge, until it decreases to a value near 0 in an oscillating way
- At the initial instants, a slight increase in power (green line) can be observed. As already explained, this is due to the link between the power and head developed by the turbine. By the way, after a short time, the drop in the flow rate prevails against the increasing head, leading to a decrease in power

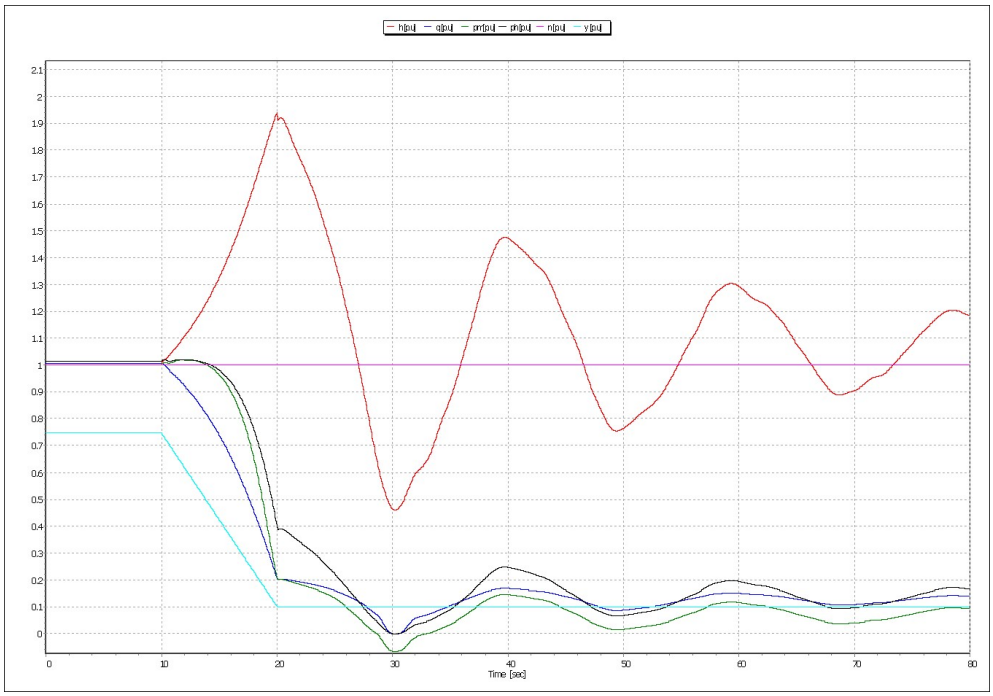


*Figure 4.13: Graph representation of the parameter's oscillations over the time*

## 4.5 SIMSEN Emergency Shut Down (ESD) simulation

As mentioned, in order to get the behavior of the turbine in case of Emergency Shut Down (ESD), the SIMSEN software has been used. The OpenModelica library turned out not to be able to simulate this scenario.

In the ESD condition the turbine is disconnected from the electrical grid due to any reason. Under this condition, the turbine is no longer coupled to the generator, and thus the effect of generator inertia is suddenly zero. The turbine starts to increase its rotational velocity until it reaches its runaway speed. This causes a water load rejection (for Francis turbines) that creates a water hammer on the upstream penstock. To stop the turbine in this condition the first thing is to close the distributor. The target of this simulation is to get the maximum pressure increase related to the turbine. This is needed to verify that this is compatible with the maximum allowable pressure of the existing penstock and if not, to study the addition of a flywheel or valves that might support the ESD.

The closing maneuver time is 10 seconds.

The turbine and generator inertia is equal to 310 $kgm^2$. The system has already been initialized according to Simulation 1 (see paragraph “4.2 The initialization 1: find the initial conditions”) i.e., the turbine distributor opening at time equal to 0 seconds has been derived for the design head and flow of the system.

The results are illustrated in the picture 4.14:

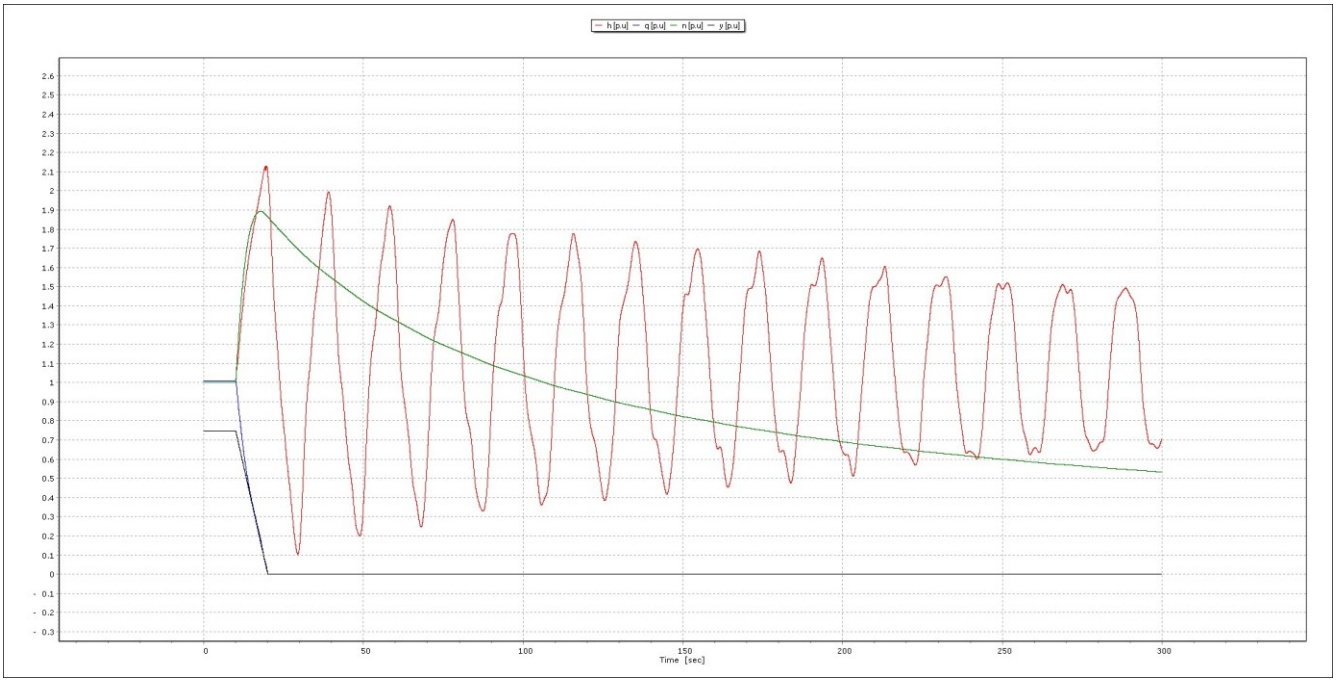


*Figure 4.14: Graph representation of the parameters in ESD*

Few comments about the results are presented below:

- In case of ESD the maximum overpressure generated by the turbine in the penstock is more than 2.1 times the design turbine head (see the first red line colour peak in the graph, approximately 320 m of water column)
- This overpressure progressively decreases with time (damping effect with time)
- When the turbine is disconnected from the grid (t=10 sec) the turbine starts to increase its velocity (green colour line)
- At the same time in order to try to stop the turbine the distributor starts to close (see the opening black colour line)
- The turbine flow follows the distributor closing trend, decreasing accordingly (blue line)

# Chapter 5: Comparison and discussion

Having optimized the simulations run for the two software, hereafter the main differences came up from the detailed comparison between the different results will be exposed.

*Flow rate*

First of all, let's see the analogy for what concerns the flow rate absorbed by the turbine.

To be able to compare the data from SIMSEN (expressed in pu) and data from OpenModelica, the latter have been extrapolated in their unit of measure ($m^3/s$), and then normalized based on the nominal value of the flow rate (equal to 1,157 $m^3/s$); in this way the two bundles of data are expressed in the same unit of measure.

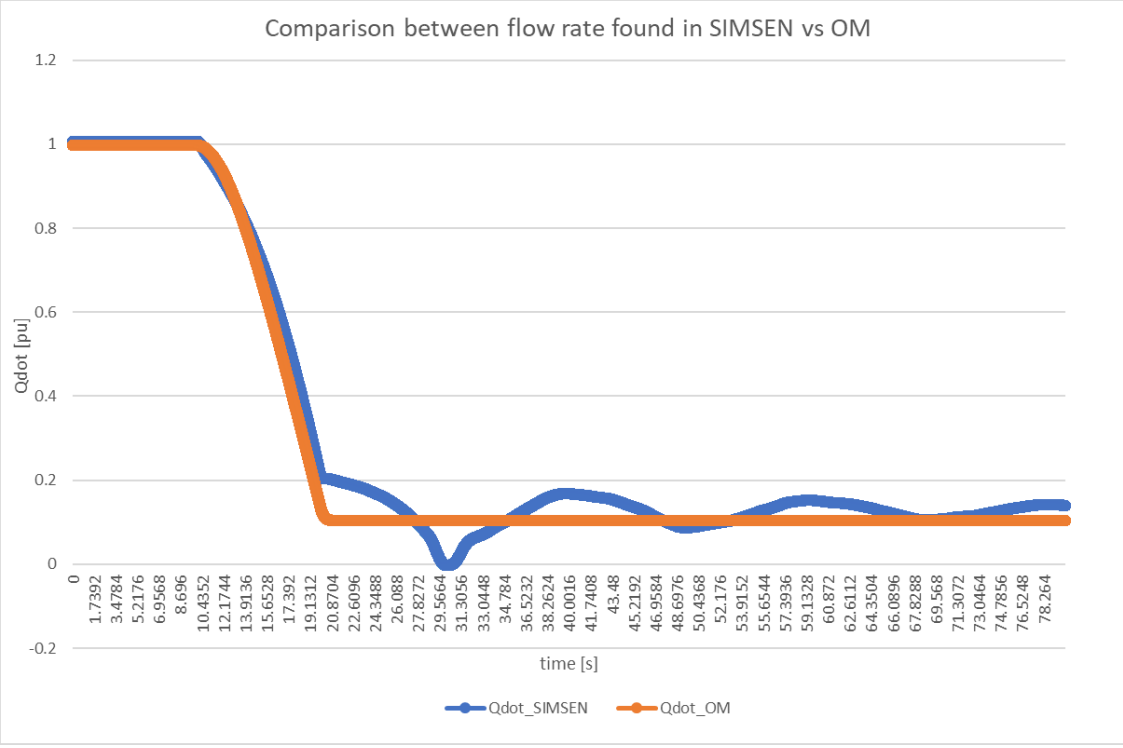


*Figure 5.1: Graphical comparison of flow rate*

Some observations can be done:

- SIMSEN oscillations are related to the fact that this software is more accurate on a numerical level in simulating the hydraulic transient. When the turbine closes, it takes some time for the flow rate to settle at the value at which it was set. As a matter of fact, after the closure, OpenModelica goes directly to the expected flow rate while SIMSEN arrives there slowly in an oscillating way. In the end the two values almost coincide

- The change in slope at closure in the SIMSEN curve is linked to the fact that, once the turbine is closed, SIMSEN no longer uses the turbine as a model, but switches to a valve behavior because otherwise it would go out of the hill charts and the simulation would no longer be reliable

*Power*

Hereafter, the analogy of the power absorbed by the turbine is described.

As before, to be able to compare the data from SIMSEN (expressed in pu) and data from OpenModelica, the latter have been extrapolated in their unit of measure (W), and then normalized based on the nominal value of the power (equal to 1548 kW); in this way the two bundles of data are expressed in the same unit of measure.

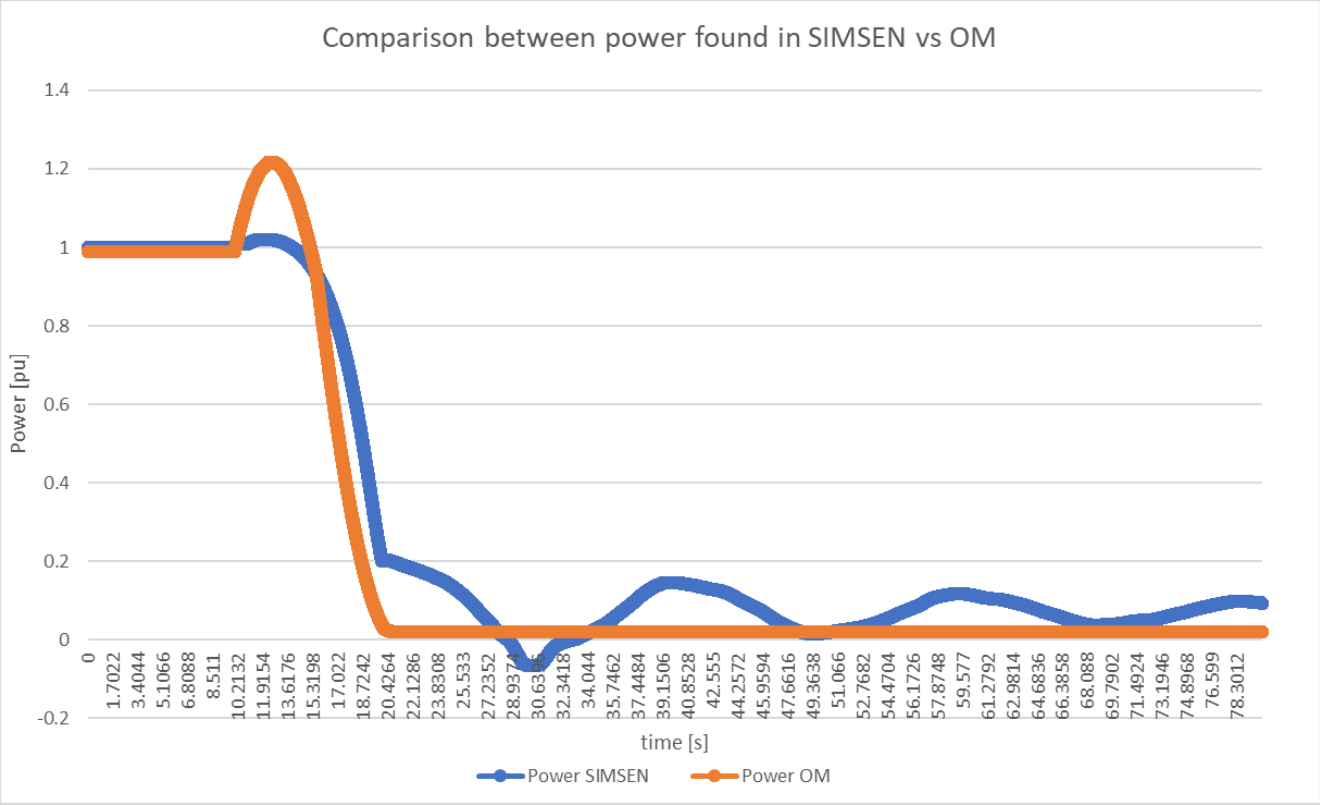


*Figure 5.2: Graphical comparison of the power*

Some observations can be done:

- As previously seen, the wave behavior of SIMSEN after closure is linked to a higher calculation accuracy compared to OpenModelica software

- The change in slope of the SIMSEN curve with the turbine closed is linked to the fact that the closed turbine is no longer described with the hill charts but is modeled as a valve. Instead, OpenModelica refers to the turbine as a valve during all the process

- The OpenModelica peak when the maneuver starts is related to the (brief) effect due to the closure; the increases head initially prevails over the flow rate, which is

actually decreasing. For a moment the power $P = H \cdot Q \cdot \rho \cdot g \cdot \eta$ is controlled by the head. As the maneuver go on, the decrease in the flow rate wins against the increase of the head, bringing the power to lower levels

- SIMSEN as well shows a slight increase in power when closing, this is more attenuated because it depends on how the turbine is shaped. In SIMSEN the behavior of the turbine is described by the hill charts (and is therefore a function of head H and flow rate Q). In OpenModelica the turbine is described by a table that describes just η=f(Q).

# Chapter 6: Conclusion

The various initial conditions to which this study is subjected have made its writing tricky but, at the same time, compelling and fascinating. The fact that the turbine must be installed in a country like Saudi Arabia has meant that elements, constants and properties that here in the local academic field are taken for granted, when applied in other areas of the world must be meticulously studied to be as precise as possible and keep faith with reality.

As far as the study of software is concerned, it has been concluded that OpenModelica can be used in academia or in the preliminary phase, but it does not guarantee the same efficiency as the other software. The development of the model with OpenHPL took time. The developers of the library itself, part of the University of South-Eastern Norway (USN), have been contacted and have confirmed the goodness of the developed model but, at least for this model in particular, equipped with upstream reservoir, pipe, turbine and downstream reservoir and which does not include additional elements, OpenModelica does not guarantee a sufficient level of accuracy.

SIMSEN, on the other hand, represents, once again, a sophisticated and sensitive software that represents a real model at its best. Working on it was a challenge; The extreme sensitivity to each input means that you have to be focused on every step if you want to have a faithful result.

Working with two different software has allowed me to appreciate the substantial differences that can exist in dealing with the same job. Different approaches have to be put in place to achieve the same result and this, I think, has given me a good capacity for adaptability.

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