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Electrical Power Engineering

Application of Design of Experiments for the Verification of a Hydro Power Plant



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Summary:

Hydropower is one of the top interest research in renewable energy towards the transition of clean and green energy, therefore, there are increasingly simulation models of hydroelectric power plant with the purpose of examining and predicting the characteristic and behavior of hydropower plant during the different operating conditions. In progress of modelling and simulating, these models need to be verified and optimized to give the high reliable simulation results. Under the vast amount of data, there are some difficulties to filter out the necessary parameters for the simulation and realize unknown source leading to difference between simulation results and reference values, therefore, it requires an organized and systematic method where "Design of Experiments" method are applied.

"Design of Experiments" (DoE) is a powerful data collection and analysis tool with planning, conducting, analyzing and interpreting experiments to evaluate the factors affecting responses of experiments. The main subject of DoE application in this thesis is simulation model of Grunnåi hydropower plant that has been built before by Dymola/Modelica in combination with OpenHPL and OpenIPSL. All of portions of this hydropower plant model are experimented according to DoE procedures with the purpose of model verification and optimization. Through performing these verification experiments, the hydropower plant model has been optimized and completed.

This thesis presents how to apply DoE method in verifying simulation models of hydropower plant under the vast amount of data as a premise for other verification experiments of associated simulation models in various of engineering field.

Preface

This thesis is the conclusion of a two-year program of Master of Science in Electrical Power Engineering at University of South-Eastern Norway and this thesis is submitted to the Department of Electrical Engineering, IT and Cybernetics at campus Porsgrunn.

As a continuation of Project – Modelling and Verification of the Grunnåi Research Power Plant in the autumn 2021, the Master’s Thesis is performed in the next semester, the spring 2022. The focus of this thesis is mainly applying experiments to verify the previous simulation model of the hydropower plant.

Firstly, I would like to express my most thankful to my supervisor, Dietmar Winkler for his investment of time, patience, and assistance in whole of the thesis’s work. His dedicated advise, guidance and encouragement play an instrumental role in the completion of the thesis. Secondly, I would like to thank Ingunn Granstrøm from Skagerak Kraft AS for sharing the information, practical values and technical solutions to the project. In addition, thanks to Kristian Nymoen for supplying and sharing the necessary operation dataset of the hydropower plant, without the data, the simulation model cannot be completed.

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Nomenclature

Acronyms

USN	University of South-Eastern Norway
DoE	Design of Experiments
OFAT	One factor at a time
PE	Percent error
MAPE	Mean absolute percentage error
T1	Turbine 1
T2	Turbine 2
G1	Generator 1
G2	Generator 2
TX1	Transformer 1
TX2	Transformer 2
TX3	Transformer 3
TX4	Transformer 4
L1	Transmission line 1
L2	Transmission line 2
L3	Transmission line 3
L4	Transmission line 4
CSV	Comma-Separated Values
OpenHPL	Open-source hydropower library
OpenIPSL	Open-instance power system library
pu	Per-unit
AC	Alternating current
DC	Direct current

Symbols

Q	Volumetric flowrate	$[m^3/s]$
V	Volume	$[m^3]$
A	Cross-sectional area	$[m^2]$
d	Diameter	$[m]$
v	Flow velocity	$[m/s]$
p	Pressure of fluid	$[Pascal]$
ρ	Density of fluid	$[kg/m^3]$
g	Acceleration of gravity	$[m/s^2]$
h	Height	$[m]$
z_{res}	Level of upper reservoir	$[m]$
z_{tw}	Level of tail race water	$[m]$
H_g	Gross head	$[m]$
H_n	Net head	$[m]$
h_f	Head loss due to friction	$[m]$
P_n	Net power	$[W]$
η_h	Hydraulic efficiency	
S_{base}	Base apparent power	$[MVA]$
V_{base}	Base voltage	$[V]$
I_{base}	Base current	$[A]$
Z_{base}	Base impedance	$[\Omega]$
P_r	Power at the runner of turbine	$[W]$
P_s	Power at the shaft of turbine	$[W]$
η_m	Mechanical efficiency	
R	Resistance	$[\Omega]$
X	Reactance	$[\Omega]$
Z	Impedance	$[\Omega]$

1 Introduction

1.1 Background

In contemporary society, there has been a raise concern in renewable energy in satisfying human's demand of energy due to the transition of more environment-friendly source of energy. There is no denying on the influence of renewable energy in contributing to the total worldwide energy and reducing the greenhouse effect and global warming. In the world's sources of renewable energy, hydropower is the biggest source and generates the most electricity [1]. According to the data from the International Energy Agency (IEA) and the US Energy Information Administration (EIA), while in 2013, it represented over 16% of the world's total energy production – in contrast other renewable sources accounted for less than 6% [1]. Because of the advantage of hydropower as renewable, efficiency and reliable source of energy as well as the source that generates the most electricity, hydropower technology is always concerned and developed and the main interest of research.

One of the countries with the highest production of electricity from hydropower around the world is Norway. Hydropower is main resource generating electricity of the Norwegian electricity system [2]. In a normal year, the Norwegian hydropower plants produce 136.4 TWh, which is 90% of Norway total power production [2]. With Norway's leadership in hydroelectric technology, Norwegian hydropower plants have always been an interest of studies in modelling hydropower plants based on associated software and tools.

A hydropower plant model is mathematical combination of each units of a real plant, which represents the same characteristic to the real system. The simulations allow doing experiments on the model to examine and predict the characteristic behavior of real plant according to the different operation conditions. There are various number of software used for modelling and simulating of hydropower plant. However, in progress of modelling and simulating, these models need to be verified and optimized to give the most reliable simulation results. In addition, facing the vast amount of data from the hydropower plant, setting up experiments on model consumes a lot of time and effort. Therefore, it is crucial to do the experiments in an organized and systematic way where "Design of Experiments" methods will be applied.

In cooperation with Skagerak Kraft, among the largest power producers in Norway that delivers about 5700 GWh of clean, renewable energy from 48 wholly or partially owned

power plants [3], the model for studying characteristics of the hydropower plant located at Seljord municipality in Telemark county of Norway during different operating scenarios was created. The main objective is to verify and optimize this hydropower plant model and contributes effective procedures to the verification of simulation models in every field of engineering.

1.2 Objectives and Scope

The thesis is based on the project work done in the first semester at the last year at USN [4]. During the project work, a simple model of a hydropower plant was made and showed a literature study about modelling hydraulic system and electrical system. However, under the vast amount of data, there are some difficulties to filter out the necessary parameters for the simulation and realize the unknown source leading to the discrepancy between simulation results and realistic measurement. Therefore, this thesis is desirable to give specific implementation steps for experiments with the purpose of verifying and optimizing the simulation model of hydropower plant.

The original task description can be found in Appendix A. To sum up, there are main objectives of this thesis:

- Familiarize with the existing Modelica model of the waterway and electrical installation.
- Familiarize with the “Design of Experiments” principles.
- Investigate the available data and parameter that can potentially tuned for given available data.
- Define and plan suitable sequence of simulation cases in order to obtain data to verify and adjust certain parameters of the models.
- Execute the planned simulation cases and adapt the models accordingly.
- Document the achieved verification and uncertainties, both in the report and in the test models.

1.3 Outline

The report has the following structure to provide a general understanding of “Design of Experiments” (DoE), the structure of hydropower plant, its simulation model and the application of DoE in verifying the model. A summary of each chapter’s content is as follows:

Chapter 2

This chapter introduces the basic concepts, principles and procedures of "Design of Experiments".

Chapter 3

This chapter contains the system descriptions of typical hydropower plant.

Chapter 4

This chapter introduces the general information of Grunnåi hydropower plant that is the main subject of the thesis.

Chapter 5

This chapter contains the information of the software that will be used in this thesis.

Chapter 6

This section contains the information of previous work.

Chapter 7

This section presents the methods that are used in the experiments.

Chapter 8

This section contains sets of experiment for simulation model verification.

Chapter 9

This chapter contains the discussion regarding to the results of experiment, measurement data and application of methods.

Chapter 10

This final chapter describes the conclusions which can be figured out from the report based on the presented data and information.

2 Design of Experiments

Experiments are performed today in many engineering and scientist field to gain the understanding and knowledge of various processes. In an engineering environment, experiments are often conducted to explore, estimate and confirm. Exploration implies understanding the data from the process. Estimation refers to determine the effects of process variables or factors on the output performance. Confirmation refers to verifying the results obtained from the experiments. Therefore, to obtain efficient experiments, the design of experiments plays an important role. [5]

This chapter introduces the basic concepts, principles and procedures of design of experiments. Design of Experiments is abbreviated as DoE throughout this chapter as well as the Master's Thesis.

2.1 Introduction

Design of Experiments (DoE) is a systematic, efficient methodology that can be effective for general problem-solving, as well as for improving or optimizing product design and manufacturing processes [6]. It is structured approach for collecting data and making discoveries. Specific applications of DoE include identify proper design dimensions and tolerances, generating math models that describe physical system behavior, and determining ideal configuration settings.

According to [7], the main uses of DoE are the following:

- Comparison: is used to select the best option among multiple alternatives.
- Variable screening: is to select important factors (variables) among many that affect performances of a system, process, or product.
- Transfer function identification: if important input variables are identified, the relationship between the input variables and output variable can be used for further performance exploration of the system, process or product via a transfer function.
- System optimization: the transfer function can be used for optimization by moving the experiment to optimum setting of the variables. By this way performances of the system, process or product can be improved.

- Robust design: deals with reduction of variation in the system, process or product without elimination of its causes. Generally, factors that cause product variation can be categorized in three main groups, external/environmental, internal or unit to unit variation.

DoE begins typically with the objectives determination of an experiment and selecting the process factors for the study. A well-chosen experimental design is the detailed experimental plan prior to doing the experiment that maximize the amount of factors for a given amount of experimental effort.

The statistical theory underlying DoE generally begins with the understanding of the process. A process is the transformation of inputs into output. In performing a designed experiment, the input factors are typically changed to observe corresponding changes in the output responses. The general model of a process or system is illustrated in Figure 2.1.

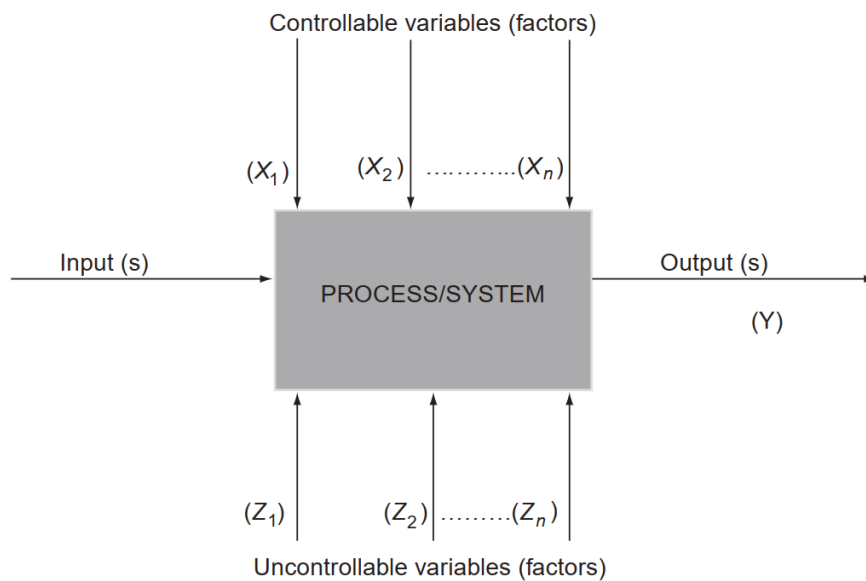


Figure 2.1: General model of process or system [5]

In variety of situations, the process variables or factors can be controlled easily while some of them are difficult to control. Controllable variables play a main role in the process characterization since it is easy to use them to control the process during an experiment. Uncontrollable variables are difficult to control therefore they can make the variability in the process performance.

2.2 Basic Principles of DoE

2.2.1 Randomization

Randomization is the practice of using chance methods to assign treatments to experimental units in a manner that protects against unintended influences on the assignments. A treatment which is one specific combinations of several factors at specific levels, are applied to a set of experimental units to plan an experiment to ensure valid statistical analysis is possible. Randomization allows experimenters to safeguard against unforeseeable and uncontrollable variables which might have mask relationships between the factors and the response. [8]

By randomizing the order in which experimental runs are done, it helps reduce the chance that differences in experimental materials or conditions strongly bias results. Randomization also lets estimate the inherent variations so the valid statistical inferences based on the data from the experiments can be made. [9]

In a designed experiment, according to [10], randomization should be applied for the following:

- The experiment runs take a roughly equal amount of time and resources to complete.
- It is possible that unforeseeable and/or uncontrollable variables could have a moderate to several affect the study results.
- There is a desire to have the separate data analyses agree from different statisticians.

2.2.2 Replication

Replication means repetitions of the entire basic experiment or a portion of it under one or more conditions. In other words, it is a process of running the experimental trials in a random sequence. Replication is very principal because it adds information about the reliability of the conclusions or estimates to be drawn from the data. Therefore, it has two important properties.

These are:

- Allowing the experimenter to gain the experimental error estimation.
- Permitting the experimenter to gain a more precise estimate of the factor/interaction effect.

It is noted that if the number of replicated is equal to one or unity, the conclusions of the effect of the factors or interactions cannot be given. Therefore, it is necessary to have sufficient the number of replicates. [5][11]

2.2.3 Blocking

Blocking is a method of eliminating the effects of extraneous variation according to noise factors, thereby improving the efficiency of experimental designs [5]. In the statistical theory of the design of experiments, the experimental units in groups or blocks, which are similar to one other, are arranged. Generally, a blocking factor is a source of variability that is not of primary interest of the experimental designs [12].

Experimenters can collect data under the same experimental conditions in the same block and determine the variability between blocks from the experimental error, which increases the precision of the experiments [5].

2.3 Experimental Designs

This section describes the most common experimental designs that are usually applied in experiments. These types of design are one factor designs, factorial designs and response surface.

2.3.1 One Factor Designs

One factor designs, also known as “one factor at a time” (OFAT), are the designs where only one factor is under investigation, and the objective is to determine whether the response different at different factor levels. The factor can be qualitative or quantitative [13]. Quantitative data refers to any information that can be quantified, counted or measured, and given a numerical value while qualitative data is descriptive, expressed in terms of language rather than numerical values [14].

In one factor designs, in the case of qualitative factors, the experiments can be performed outside the tested levels, and only the effect of the factor on the response can be determined. On the other hand, data from the experiments where the factors is quantitative can be used for both effect investigation and prediction, provided that sufficient data are available. [13]

OFAT is a traditional approach to experimentation and is preferred in situations where the data is cheap and abundant. Experimenters can decide upon the number of experiments to be conducted.

2.3.2 Factorial Designs

In this type, multiple factors with two or more, are investigated simultaneously during the experiments. Similar as one factor designs, qualitative and/or quantitative factors can be considered. The objective of these designs is to identify the factors that have a significant effect on the response, as well as investigate the effect of interactions of factors [13].

According to [15], the main advantages of using factorial experimental design is:

- Efficiency: Factorial designs are significantly more efficient and can provide more information at a similar or lower cost by using multiple factors simultaneously instead of using each factor in turn.
- Low-cost: Additional factors can be examined without having to bear additional cost for extra experiments.
- Comprehensive results: The effects of a factor as an estimate at several levels of other factors can be calculated and helps yield conclusions that are valid over a range of different experimental conditions.

Factorial designs has also the common following types, general full factorial designs, two level factorial designs and two level fractional factorial designs.

General Full Factorial Designs

General full factorial designs are applied where each factor in experiments can have a different number of levels, and the factors can be quantitative, qualitative or both [13]. The number of experiment runs can be calculated for a general full factorial designs by:

$$n = X^k \quad (2.1)$$

Where:

n - Number of experiment runs

X - Number of levels or settings of variables or factors

k - Number of variables or factors

Two Level Full Factorial Designs

These are factorial designs where the number of levels of each factor is restricted to two. According to Equation (2.1), full factorial two level experiments are also known as 2^k designs. Restricting the levels to two and running a full factorial experiment reduces the number of treatments and allows experimenter for the investigation of all the factors and their interactions [13]. The 2^k full factorial design is particularly use full in the early stage of experimental work, especially when the number of process parameters or design factors is less than or equal to 4. In the experiments, if all factors are quantitative, the data from such experiments can be used for predictive purposes, provided a linear model is appropriate for modelling the response.

Two Level Fractional Factorial Designs

This design is a special category of two level designs when very often experimenters do not have adequate time, resources and budget to carry out full factorial experiments. In this design, not all factor level combinations are considered and used, experimenters can choose which combination are to be excluded.

2.3.3 Response Surface

A response surface design is a set of advanced design of experiments that help better understand and optimize the response. This design is often used to refine models after having the determination of important factors [9]. It is very useful for:

- Understanding or mapping a region of a response surface.
- Finding the levels of variables that optimize a response.
- Selecting the operating conditions to meet specifications.

2.4 DoE Steps

In this section, the steps to perform experiments are given. To gain good results of experiments, the key steps of DoE can be divided into the following stages. These are:

- Objectives recognition
- Selection of response
- Selection of process variables

- Evaluation criteria recognition
- Selection of experimental design
- Performing the experiment
- Interpreting experimental results
- Conclusions and recommendations

2.4.1 Objectives Recognition

A clear statement of problem or the objectives for an experiment can be given to gain the understanding of what needs to be done. The statement should contain a specific and measurable objective that can optimize the practical value. Clearly defined goals or objectives of the experiments are important and have influences to the later steps of experiments. Prioritization of the objectives can help determine the direction to continue according to the selection of the relevant factors, responses and the particular design [5].

2.4.2 Selection of Response

The selection of a suitable response for the experiment is important to the success of experiment. The response, or output of experiment which are potentially influenced by the factors and their respective levels, should be certain to provide the useful information about the process under study. In common experiments, the important outcomes are measured and analyzed to determine the factors and their settings that will provide the best overall outcome for the quality characteristics. [16]

2.4.3 Selection of Process Variables

This stage is to consider the factors or the inputs to the process that may influence the performance of a process or system. This stage is crucial of experimental procedure since if the important factors are left out of the experiment, then the response of the experiment will not be accurate and useful for any later improvement actions [5].

The process variables have levels or settings that are the hold values during the experiments. Determination of levels of each factors or their level combinations would assist in studying the influence of process variables on the response.

2.4.4 Evaluation Recognition

After finishing the selection of the objectives of experiments, process and response variables, the experimental evaluation criteria is given before conducting experiments that is the criterion for evaluate whether the experimental result accurate or not. The success or failure of experiments is based on this criteria. There are many criteria, and almost them depend on the design and type of experiment. Some are listed:

- Accuracy: refers to how close or far of a given set of experimental result to the true value or reference value. The accuracy can be expressed via the percent error (PE) that is the difference between the experimental values and the actual values. Smaller PE mean the experimental values are close to the accepted or real value. According to [17], the percent error (PE) can be derived by:

$$PE = \frac{|\text{Actual Value} - \text{Experimental Value}|}{\text{Actual Value}} \times 100\% \quad (2.2)$$

- Precision: It is measure of the scatter of results of several observations and is not related to the true value. It is a comparative measure of observed values and is only a measure of the random errors that is expressed as the standard deviation of observed values from repeated results under identical condition. [5]

2.4.5 Selection of Experimental Design

The choice of an experimental design depends on the objectives of the experiment and the number of factors to be investigated. If the above stages are done correctly, this step is relatively easy. Based on experimental design, number of trial runs can be estimated that is important for experiments taking a lot of budgets and time to perform. Some of common experimental designs are listed in Section 2.3.

2.4.6 Performing the Experiments

In this stage, the planned experiments are carried out and conducted. When running the experiment, it is vital to monitor the process carefully to ensure that everything is being done correctly according to the plan. In addition, the performance of experiments should avoid the external sources of noise during this stage that can be destroy experimental validity. In progress of performing the experiments, the responses of experiments are recorded or collected to analyze in the next stage.

2.4.7 Interpreting Experimental Results

After having collected responses of experiments, the experimental results should be analyzed to lead to the final conclusions of the experiments based on the given objectives. There are several methods assisting in interpreting experimental results, the most common and simplest method is graphical representation that is an attractive method of visualizing numerical data.

Graphical representation is useful aids to portray the results of experiments. The general principle is to convey as much information as possible in the figure, with the constraint that the reader is not overwhelmed by too much detail [18]. There are many different types of graph in graphical representation, some of common are line graph, dot plot, scatter plot, bar chart or pie chart [19].

2.4.8 Conclusions and Recommendations

This stage is to carry out the practical conclusions about the experimental results and recommendation for the next actions. The conclusions are given is based on the evaluation criteria as step 4. The confirmation testing is also performed in this stage to validate the conclusions from the experiment.

2.5 Statistical Background of DoE

This section illustrates the statistical background of DoE.

2.5.1 Linear Regression

In statistics, linear regression is a linear approach for modelling the relationship between a scalar response and one or more explanatory variables. The case of one explanatory variable called simple linear regression, and for more than one, the process is called multiple linear regression. [20]

According to [21], a general multiple linear regression model with one response and i variables is expressed as:

$$y = \beta_0 + \beta_1x_1 + \beta_2x_2 + \cdots + \beta_ix_i \quad (2.3)$$

where:

y - Response variable

$x_{j,j=0,1,\dots,i}$ - Input variables or input factors

$\beta_{j,j=0,1,\dots,i}$ - Regression coefficients or parameters, represents expected change in response variable per unit change in input variable

The main goal of regression is to construct an efficient model to predict dependent attributes from a bunch of attribute variables and linear regression is a very simple algorithm that can be implemented very easily to give satisfactory results. It has a considerably lower time complexity and the mathematical equations of linear regression are also fairly easy to understand and interpret.

3 System Description

This chapter provides a basic overview structure of hydropower system. A hydropower system is a combination of facilities and electromechanical equipment with the operation principle of converting the kinetic, potential energy of water first into mechanical energy and then electrical energy.

According to [22], there are four main types of hydropower plants:

- Run-of-river hydropower: this type uses flowing water from a river through a canal or penstock to spin a turbine, typically has no water storage facility. Since no large dam needs to be built for storage, they are quite cheaper than other types and are popular for various small-scale hydropower applications.
- Storage hydropower: as known as a large-scale system, the water is stored in a reservoir by using a dam and electricity is generated by releasing water from reservoir through turbine. This can offer capability of control over production according the demands of the system and is not depended on the inflow for long times.
- Pumped storage hydropower: is cycled between a lower and upper reservoir by pumping due to the change of electricity demands. It means that the water from the high to the low reservoir when having a high demand and when there is a low demand, the water is pumped from a lower reservoir to a higher one. The distinction is that the pumped storage systems consume the energy from the grid to lift the water up, and return most of this energy to grid later.
- Offshore hydropower: is a growing group that uses tidal currents or the power of waves to generate electricity.

The following work considers only storage hydropower type that has the typical structure shown in Figure 3.1. According to the typical structure of storage hydropower plant, the installed components begin at the dam and end at the outflow. Water is stored at the reservoir by dam, flowing through the trash rack to enter the head race tunnel/conduit via the intake gate and further to the penstock before reaching the main valve that has the function of controlling the water force going into the turbine. The turbine is connected with the generator by the shaft coupling element and the mechanical power from turbine is transferred to generator that converts mechanical power into electrical power. The amount of water flowing into the turbine is led out to the downstream through the outflow.

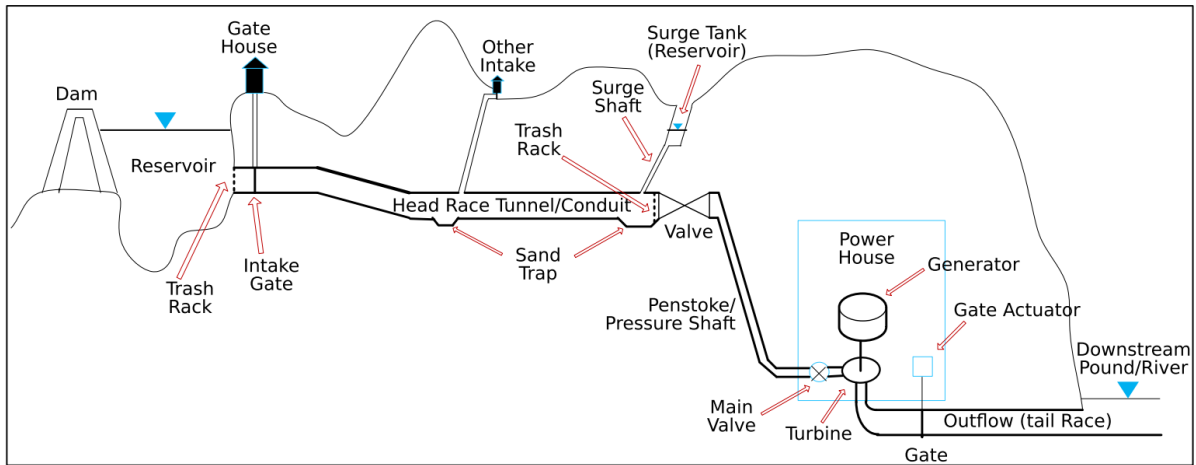


Figure 3.1: Typical structure of storage hydropower plant [23]

Hence, the hydropower system can be divided into two main system, hydraulic system and electrical system. In addition, the hydraulic system includes three parts, inlet system, hydropower turbine and outlet system while the electrical system consists of generator as the main components and other electrical components.

3.1 Hydraulic System

In hydraulic system, flowrate that is defined to be the volume of fluid through an area during a period of time, is an important quantity. According to [24], flowrate through pipeline can be expressed by :

$$Q = \frac{V}{t} = \frac{Ad}{t} = vA \quad (3.1)$$

Where:

Q - Volumetric flowrate [m^3/s]

V - Volume [m^3]

A - Cross-sectional area of flow [m^2]

d - Diameter of pipeline [m]

v - Flow velocity [m/s]

t - Time [s]

In addition, according to [25], the fluid pressure is proportional to the height of fluid and can be expressed by:

$$p = \rho gh \tag{3.2}$$

Where:

p - Pressure of fluid [*Pascal*]

ρ - Fluid density [kg/m^3]

g - Acceleration of gravity [m/s^2]

h - Height of the fluid [m]

Roughness Factor Water conveying represents the most important of hydropower projects, therefore factors affecting to the efficiency of water conveying are the main concern in improving the efficiency of the system. One of basic criteria to improve the efficiency of water conveying is decreasing friction loss of water flowing in tunnels or pipes that are the main components of conveying water. The friction loss depends on both cross-sectional area and roughness of tunnels or pipes. Figure 3.2 [26] shows the poor and good quality of roughness factor in the typical of water tunnel.



a. Relatively good quality tunnel contour (Upper Tamakoshi Project, Nepal)

b. Relatively poor quality tunnel contour with excessive over-break (Khimti Project, Nepal)

Figure 3.2: Good and poor roughness factor in water tunnel [26]

The flow surface of waterway system, tunnel or pipe, is typically made up for different materials as gravel, concrete, rock or steel. In addition, the pipe materials and common pipe roughness values can be illustrates in Table 3.1.

Table 3.1: Pipe roughness value according to pipe material [27]

Material	Pipe roughness values [mm]
Concrete	0.3 – 3
Cast Iron	0.26
Galvanized Iron	0.15
Asphalted Cast Iron	0.12
Commercial or Welded Steel	0.045
PVC, Glass, Other Drawn Tubing	0.0015

According to research project about roughness value waterway tunnel [26][28], the roughness parameter of tunnel can be determined based on the material of tunnel and geographical structure of hydropower plant.

3.1.1 Inlet System

The inlet system is the important part of hydroelectric power plant that is the system of conveying water from the natural resource (river, reservoir) to the hydraulic turbines of the power plant. Reservoirs usually have a large height difference from the base of a hydroelectric power plants to take full advantage of the power of water flowing from the top.

The inlet system includes the following components: dam, reservoir, trash rack, intake gate, headrace tunnel/conduit, sand trap, surge tank, surge shaft, penstock/pressure shaft and main valve.

Dam

Dam is used to create a reservoir in order to contain the water and create a water drop that is used to produce energy. Most common dams can be made by concrete or earth. There are different type of dams, some of them are listed in following:

- Gravity dam: is a large dam and usually made from concrete, with the function of holding the large amounts of water in order to create reservoirs. To avoid suffering the failure by the vast amount of water, this type of dam must be built on solid bedrock.
- Embankment dam: is usually made by various materials such as soil, sand clay or rock. Therefore, it can be known as earth-filled or rock-filled dam.

Reservoir

A reservoir has the main function of storing water that is the main working body of the hydropower system. A reservoir can also be formed basis of a lake or a river. The water height level in the reservoir is one of the major factors in determining how much electricity can be generated from hydropower system. Since the water, held at a higher elevation, has a certain amount of potential energy that can be converted to rotational motion of turbines when the water falls.

Trash Rack

The trash rack can be installed in order to prevent trees, branches or stones from entering to the conduit system to the turbine that can cause damage to the turbine or decrease the efficiency of conveying water through the tunnel or conduit. Trash rack is usually arranged at both ends of headrace tunnel/conduit with the purpose of turbine protection. [29]

Intake Gate

A intake gate is arranged to shut off the water flowing into the tunnel or conduit system when the conduit system need to be maintenance or emptied. The intake gate is usually controlled from the gate house that is often built at reservoir area. [29]

Headrace Tunnel/Conduit

The headrace tunnel/conduit or waterway is a system with the function of transferring the water from the reservoir to the turbine that is usually installed between the reservoir and the penstock. Depending on the structure of the hydropower plant, it can be tunnel or conduit.

Sand Trap

The sand trap is a part of headrace tunnel/conduit in order to reduce the erosion processes on the mechanical components of the valves and turbine. In order to prevent bypassing of sand, the sand trap should be emptied at fixed time intervals set in accordance with the hydropower plant operation and maintenance schedule. [29][30]

Surge Tank

The water flowing through the headrace tunnel/conduit, it can accelerate or decelerate that causes pressure variations with magnitude exceeding the nominal pressure in the waterway, therefore, it leads to the load changes causing the mass oscillations. The large oscillations is the culprit called water hammer effect. The function of surge tank is reduce the water hammer pressure variations and keep the mass oscillations within acceptable limits and decrease the oscillations to stable operation as soon as possible. [29][30]

Surge Shaft

Surge shaft is a surge tank with small cross section area. It can be installed additionally to the surge tank. [30]

Penstock/Pressure Shaft

Penstock/Pressure shaft is a pipe either welded of steel plates, or made of concrete or wood. This pipe is arranged between the headrace tunnel/conduit and the main vane with the purpose of controlling the water into the turbine. The penstock can be lined and unlined, depended on the quality of the rock. If the rock quality is sufficiently high, an unlined penstock is more economical and technical suitable. [29][30]

Valve

This is a gate vane installed at the head of penstock/pressure shaft which is to control or isolate the flow of water into the penstock.

Main Valve

The main valve is arranged prior to the turbine to control the flow of fluid entering the turbine It might be to prevent the damage on the turbine blades and to control fluctuating pressure entering the turbine. Therefore, to maintain the speed of the turbine constant the flow is controlled by this main valve. Depending on the water head and capacity of turbine, the type of main valve may be a gate, butterfly valve, gate valve or a spherical valve.

3.1.2 Turbine System

Water turbines are used as a machine that convert directly the hydraulic power to the mechanical power on the machine shaft. According to Figure 3.3, the hydraulic power is represented by a water flow from an upper level to a lower level that the difference between the level of the upper reservoir z_{res} [m] and the level of the tail water z_{tw} [m] can be defined as the gross head [31].

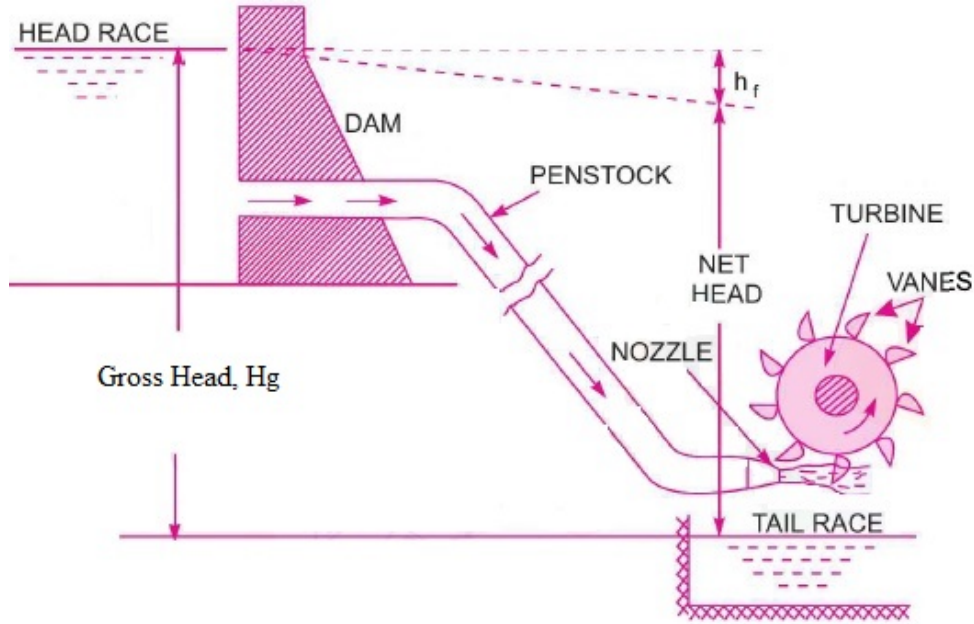


Figure 3.3: Layout of illustrating the relationship between the gross head, net head and head loss [31]

The gross head H_g [m] can be calculated as:

$$H_g = z_{res} - z_{tw} \quad (3.3)$$

The net head H_n [m] can be calculated as:

$$H_n = H_g - h_f \quad (3.4)$$

Where h_f [m] is the head loss due to friction.

The turbine selection is depended on the site conditions, flowrate and hydraulic head, which are suitable for different applications. Turbines are generally divided into three main groups based on operation principle; reaction, impulse and mixed flow turbines.

For these turbine types, according to [32], the available power supplied by the water at the inlet of the turbine can be expressed by:

$$P_n = \rho Q g H_n \quad (3.5)$$

Where:

P_n - Net power [W]

ρ - Fluid density [kg/m^3]

Q - Water flowrate [m^3/s]

g - Gravitational acceleration [m/s^2]

H_n - Net head [m]

According to [31], hydraulic efficiency is basically defined as the ratio of power given by water to the runner of turbine to the power supplied by the water at the inlet of the turbine and can be expressed by Equation (3.6).

$$P_r = \eta_h P_n \quad (3.6)$$

Where:

P_n - Net power [W]

P_r - Power at the runner of turbine [W]

η_h - Hydraulic efficiency

In addition, power given by water to the runner of turbine will be transmitted to the shaft of the turbine. Mechanical power available at the shaft of the turbine will be less than the power delivered to the runner of the turbine due to mechanical losses [31] and can be expressed by:

$$P_s = \eta_m P_r \quad (3.7)$$

Where:

P_s - Power at the shaft of turbine [W]

P_r - Power at the runner of turbine [W]

η_m - Mechanical efficiency

Impulse Turbine

The working principle of impulse turbine is using the high-velocity jets of water from nozzles directed into buckets in the runners. There is only impulse forces being transferred by the direction changes of the flow velocity vectors with no pressure difference between inlet and outlet [29].

The most common of this type is Pelton turbine that is used frequently for high head hydropower systems. A Pelton turbine is preferred to be used with a low flowrate and the large height difference (300-400m). [33]

Nozzle (Needle) Valve

Nozzle (needle) valve is a type of valve that is used to perfectly control the flowrate of fluids and this valve is used commonly in impulse turbine to control the flowrate into turbine. The adjustments are gradual and smooth for controlling the flowrate, however, they can also be used as a reliable shut-off valve. In hydropower system, there are plenty of nozzles with the purpose of controlling the flowrate into turbine blades. In this way, it is possible to control the running speed of the turbine as well as help the turbine achieve a stable speed as quickly as possible. According to [34], the number of nozzle has the highest influence on the efficiency of the turbine for generating power, therefore, the number of nozzle need to be calculated and designed carefully.

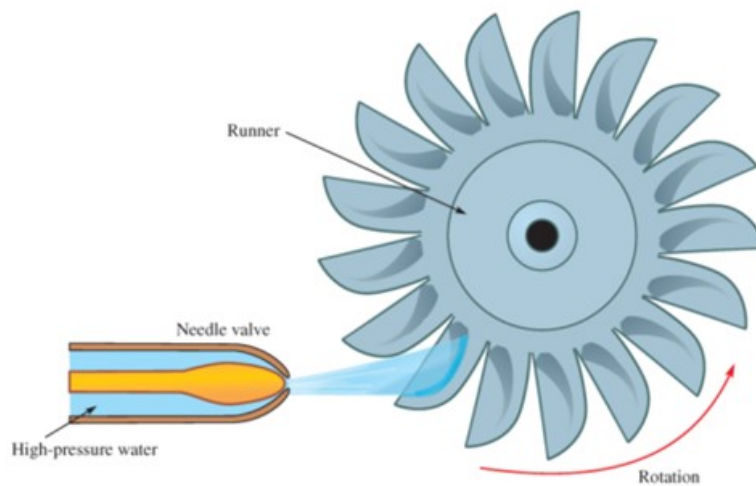


Figure 3.4: Needle vane turns hydraulic head into a high velocity stream of water which hits the turbine runner and makes it spin [35]

The opening value of nozzle is usually expressed as percentage from 0% to 100% of the valve, 0% means the valve is closed with no flowrate and 100% means the valve is fully opened. These values are changed to control the running speed of turbine due to the different operating condition of the hydropower plant.

Reaction Turbine

Reaction turbines use a drop in pressure between the inlet and outlet of the runner as known as the reaction part transferring energy from the flow to the mechanical energy. When the water enters the turbine runner, a part of the available energy of water is converted into kinetic energy, and the remaining part is converted into pressure energy. Pressure varies throughout the turbine. At the entrance of the turbine, the pressure is much higher than the pressure at the exit. [29]

The typical turbine in this group is Kaplan turbine, which is preferred to be used in very large flowrate and low height difference (<100 m). [36]

Mixed Flow Turbine

The mixed flow turbine design combines concepts of two different types of turbines, impulse turbine and reaction turbine. This is why the name “mixed flow turbines” is given. In this type, there are two effects cause the energy conversion. Firstly it follows the pressure difference between inlet and out of the runner as known as reaction part. Secondly changes in the directions of the velocity vectors of the flow through the canals between the runner blades transfer impulses forces. It is denoted the impulse part of the energy conversion. [29]

The typical turbine in this group is Francis turbine, which is preferred to be used in medium flowrate and medium height difference (100-300m). [33]

3.1.3 Outlet System

The outlet system can consist of tunnel or conduit or both of them which is aimed to transfer the water from the turbine to the downstream (tail water). The design of outlet system is depended on the geographical structure and the types of turbine used in the hydropower plant.

3.2 Electrical System

This section introduces main components of electrical system of typical hydropower plant such as generator and transformer.

In hydropower plant, generator converts mechanical power from the shaft of turbine into electric power. The electricity generated from hydropower plant is distributed to power grid through transmission system. The voltage drop across this transmission system is taken into account. To consider this voltage drop, per-unit system is applied.

Per-unit system In electrical power system analysis, a per-unit system is the expression of system quantities as fractions of a defined base unit quantity that is applied broadly in analyzing in the power system containing large numbers of devices [37]. The quantities of power system such as power, voltage, current, impedance and admittance is transferred to per-unit system with same symbol (pu) for convenience of calculation through Equation (3.8) [37]. These quantities are specified as multiples of the chosen base values,

different quantities have different base values. According to [37], base values in three-phase system can be expressed by Equation (3.9) and Equation (3.10).

$$\text{Per-unit} = \frac{\text{Actual value in any unit}}{\text{Base value in the same unit}} \quad (3.8)$$

$$S_{base} = \sqrt{3}V_{base}I_{base} \quad (3.9)$$

$$Z_{base} = \frac{V_{base}}{\sqrt{3}I_{base}} \quad (3.10)$$

Where:

S_{base} - Base apparent power [VA]

V_{base} - Base voltage [V]

I_{base} - Base current [A]

Z_{base} - Base impedance [Ω]

Voltage drop Electrical power transmission can be defined as the bulk movement of electrical energy from a generating site, such as a power station or power plant, to an electrical substation where voltage is transformed and distributed to consumers or other substations [38]. The interconnected lines that enable the movement of electrical energy are known as a “transmission network” and these form an electrical power transmission system [38].

A voltage drop in a transmission line or transmission system causes a reduction in the receiving-end voltage compared to the sending-end voltage. This voltage drop is mainly influenced due to the transmission line parameters, resistance (R), inductance (L), capacitance (C), and shunt conductance (G). These parameters offer impedance to the flow of current and voltage drops throughout the length of the transmission line. There is a uniform distribution of R, L, and C throughout the length of the transmission line. The series impedance is formed by the resistance and inductance, whereas the capacitance and shunt conductance between the conductors form the shunt impedance. The influence of these line parameters on the voltage drop varies with the length of the transmission cables [39].

Transmission line modeling is crucial step towards achieving better transmission efficiency. These transmission models present an equivalent circuit of the actual transmission line that give better insight into the behavior of the transmission lines. The overhead transmission lines are modeled using the line parameters R, L, and C to analyze performance

and determine voltage drop as well as transmission efficiency. The effects of line parameters on the transmission system differ with voltage grade and length of the transmission line [39].

Table 3.2 gives the typical classification of overhead transmission lines and the line parameters considered in the modeling.

Table 3.2: Classification of transmission line and the line parameters considered in its modeling [39]

Type of transmission line	Length [km]	Voltage range [kV]	Line parameters considered
Short transmission line	<50	<20	R, L
Medium transmission line	50-150	20-100	R, L and C
Long transmission line	>150	>100	R, L and C

3.2.1 Generator

Generators is the key component of hydropower plant that convert the mechanical energy from the turbine shaft into electrical transferring to customers via the power grid. There are two common types of generator depending on required runner speed and power station characteristics; synchronous generators and asynchronous generators.

Synchronous generator excitation is independent of the grid, so synchronous generators can build up voltage without grid connection [40]. While, Asynchronous generators are unable to regulate voltage output and are mechanically driven at a speed higher than system frequency (synchronous speed); if isolated from the grid they cannot produce power because their excitation energy comes from the grid [40].

Each hydropower generator is customized for each project, to ensure enhanced performance according to site conditions and operators' needs. Under any operating condition, the generator is optimized to run smooth to reduce structural stress and improve reliability for the life time of the turbine [40].

3.2.2 Transformer

A transformer is a device that transfers electric energy from one alternating-current circuit to one or more other circuits, either increasing (stepping up) or reducing (stepping down) the voltage [42].

The transformer is categorized on the basis of a number of turns in the primary and secondary winding. The step-up transformer transforms a low voltage, high current AC into a high voltage, low current AC system. In this step-up type, the number of turns in the secondary winding is greater than the number of turns in primary winding. The



Figure 3.5: Generator unit at typical hydropower plant [41]

step-down transformer converts a high primary voltage associated with the low current in a low voltage, high current that has the number of turns in the primary winding is greater than the number of turns in secondary winding. [43]

In hydropower plant, transformer is used to step up voltage of electric generated from generator. Then, the electric is distributed by transmission system to substations where voltage of electricity can be step up or step down.

4 Grunnåi Power Plant

In this chapter, there is a description of Grunnåi hydropower plant. Grunnåi power plant is located in Seljord municipality and is part of the power production system in the Skiensvassdraget watercourse. The Grunnåi watercourse primarily runs through Seljord municipality in Telemark county. Its outlet is from the east side of the valley at Vallaråi river in Flatdal. The source of the watercourse is Slåkåvatn lake on Litfjell mountain. [44]

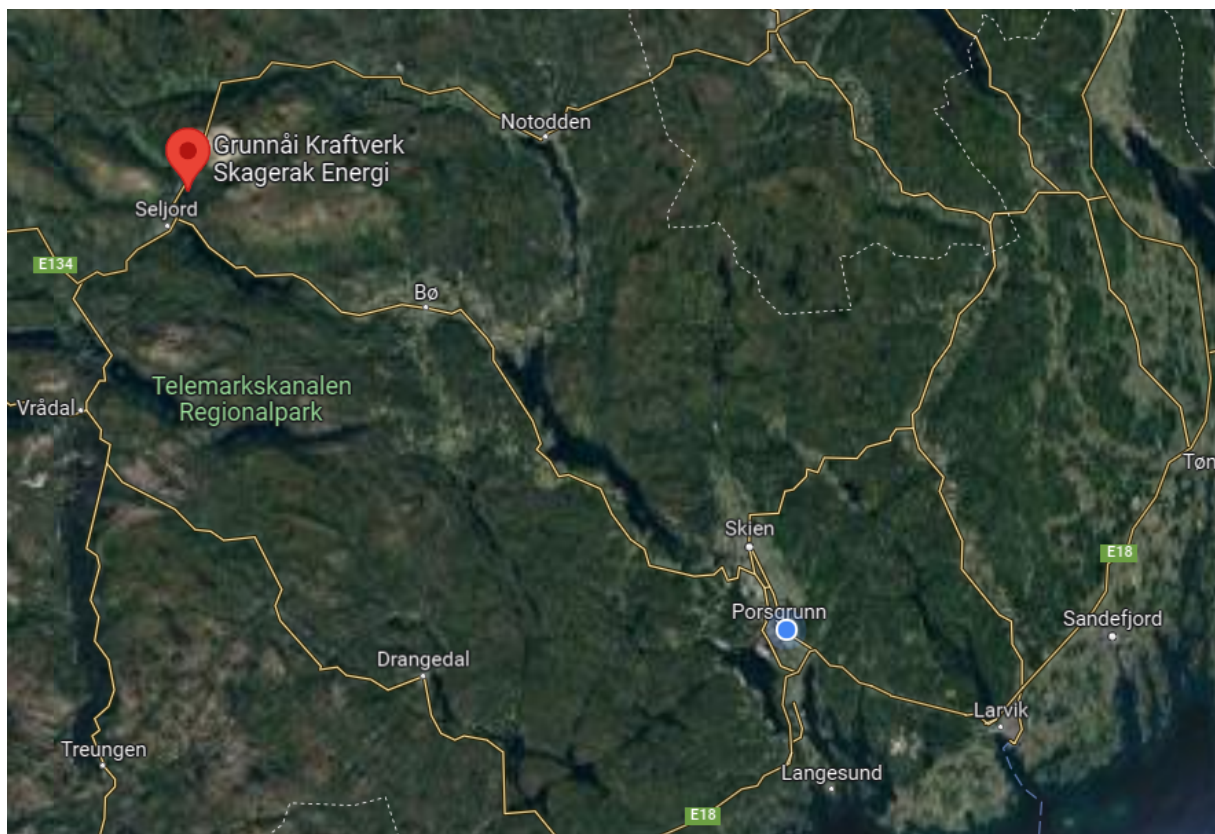


Figure 4.1: Screenshot of the map showing location with USN at blue point and Grunnåi power plant at red point [45]

The power plant utilizes a waterfall height of 387 meters for two Pelton turbines connected with two respective generators, turbine 1 (T1) is connected with generator 1 (G1) and

turbine 2 (T2) is connected with generator 2 (G2). G1, original generator has an installed capacity of 15.1 MW and an annual output of 55 GWh, while G2, an extra generator, has an installed capacity of 10.2 MW and an annual output of 11 GWh.

4.1 Hydraulic System

4.1.1 Geometry Data

The geometry data of this hydropower plant are provided in Table 4.1 following the waterway structure of the hydropower plant. It should be noted that the structure of the waterway is similar to that presented in Figure 4.2. With the general information shown in Table 4.1, the water from reservoir is conveyed to the power plant by the waterway system containing different geometry parts (lengths, slope, etc.) consisting of two blasted tunnels, "1" and "2" that then connected with a steel pipe conduit "3". This conduit is branched into two separated ways, "4+5" and "6+7" into two respective turbines, "T1" and "T2". Water discharged from two turbines through the respective outlet paths "8" and "9" and flows to the downstream, Vallarâi river through outlet system containing outlet tunnel "10" connected with culvert "11".

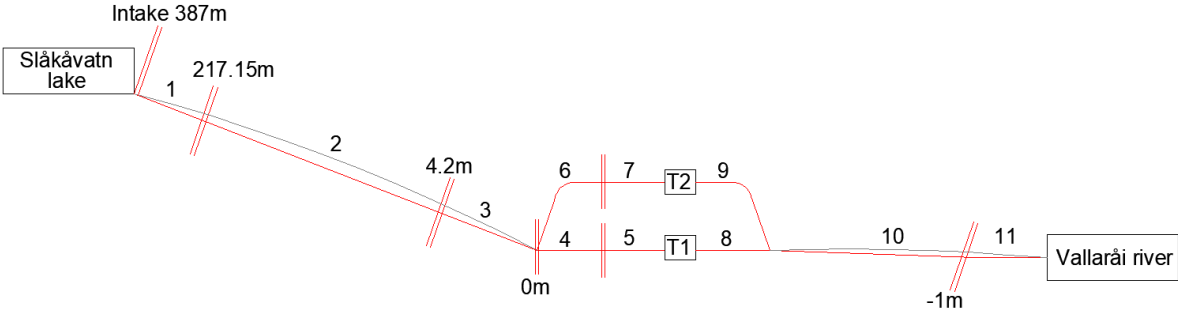


Figure 4.2: Simplified overview of the waterway in Grunnâi power plant

Table 4.1 presents the diameter values of each units in waterway of the plant. However, not all of the waterway units (e.g., Tunnel_1, Tunnel_2) are circular conduits, which means that the components representing for these unit in simulation model need to have the same cross-sectional area, the additional information can be shown in Appendix B. In addition, the parameters of turbines using in this hydropower plant can be shown in Table 4.2. These turbines are Pelton turbine and both of them have 5 nozzles.

Table 4.1: The waterway geometry, Grunnåi power plant

Object elements	Index	Length [m]	Diameter[m]
Tunnel_1 (Tunnel part 1)	1	110	5.8
Tunnel_2 (Tunnel part 2)	2	1450	5.8
Conduit	3	160	1.2
IntakeT1_1 (Intake to T1 part 1)	4	25	1.2
IntakeT1_2 (Intake to T1 part 2)	5	1.5	0.8
IntakeT2_1 (Intake to T2 part 1)	6	20	1.2
IntakeT2_2 (Intake to T2 part 2)	7	1.5	0.6
OutletT1 (Outlet of T1)	8	1.5	3
OutletT2 (Outlet of T2)	9	1.5	3
Tunnel_3	10	460	3
Culvert	11	58	2

Table 4.2: Turbines nominal operational values, Grunnåi power plant, Grunnåi power plant

Object elements	Nominal head [m]	Nominal flowrate [m^3/s]	Nominal power[MW]
T1	385	4.42	15.00
T2	389	3.08	10.76

4.1.2 Measurement Data of Hydraulic System

The measurement data in Grunnåi hydropower plant has been done using the HydroCord [46] and SCADA monitoring system [47]. The measurements are taken from various sensors located at the power plant, measure quantities of each unit according to the operation of the power plant. There are about hundreds of measured quantities from monitoring systems such as turbines oil temperature, water temperature, etc.

It is noted that not all measured quantities can be used in the simulation model. Among these variables that provide the information for simulation model experiments, these quantities are filtered and then be used for model experiments with the target of optimisation and validation. Table 4.3 shows the necessary quantity names and then, based on these quantity names, the detailed measurement name of sensor can be filtered.

Table 4.3: The necessary measurement quantity name for experiments

Quantity name	Unit
Nozzle opening value	%
Water flowrate	m^3/s
Water pressure	bar
Generated power	W

According to the quantity names of model shown in Table 4.3, the measurement name of available sensors in the power plant are extracted. Table 4.4 shows the signal of sensors at measurement positions based on the element number of Figure 4.2 that match the quantity names used for the simulation model of hydraulic system.

Table 4.4: The name of measurements corresponding to the location of the measurement matching the name of necessary quantities

Index	Measurement name	Unit
3	Water flowrate	m^3/s
3	Water pressure	<i>bar</i>
4	Water flowrate	m^3/s
6	Water flowrate	m^3/s
6	Water pressure	<i>bar</i>
T1	Generated power	W
T1	5 nozzles opening value	%
T2	Generated power	W

Measurement values are provided by Skagerak Kraft AS in different period of time in various operation condition of the power plant. This means that they have to be handled individually and have no cross-correlations.

Due to the tolerances of the sensors used in the system being negligibly small compared to deviations caused by model inaccuracies, the measured values from Table 4.4 are considered as accurate and valid values.

The reference technical data about flowrate and pressure sensors, which are commonly used in a typical hydropower plant, can be shown in [48][49] and according to this technical data, Table 4.5 shows the tolerances of these types of sensors.

Table 4.5: Tolerances in full scale (FS) measured range of sensors

Sensors	Tolerance
Pressure measured sensor	$\pm 0.25\%$ FS
Flowrate measured sensor	$\pm 0.5\%$ FS

4.2 Electrical System

The electrical system located in Grunnåi power plant includes main components as generators and transformers. There are two generators installed in the hydropower plant, G1 and G2 with different output capacity. The capacity of G1 is 15.1 MW while the capacity of G2 is 10.2 MW. Two these generators output 6.6 kV voltage which is stepped to 22 kV

through two respective transformers, transformer 1 (TX1) and transformer 2 (TX2) and then, the power will be transferred by transmission lines, L1, L2, L3 and L4 before being voltage increased by transformer 3 (TX3) and transformer 4 (TX4) in the respective lines. In practical, the load supplied by G2 is back-up by G1. The parameters of electrical units in Grunnåi hydropower plant based on Figure 4.3 can be shown in [4].

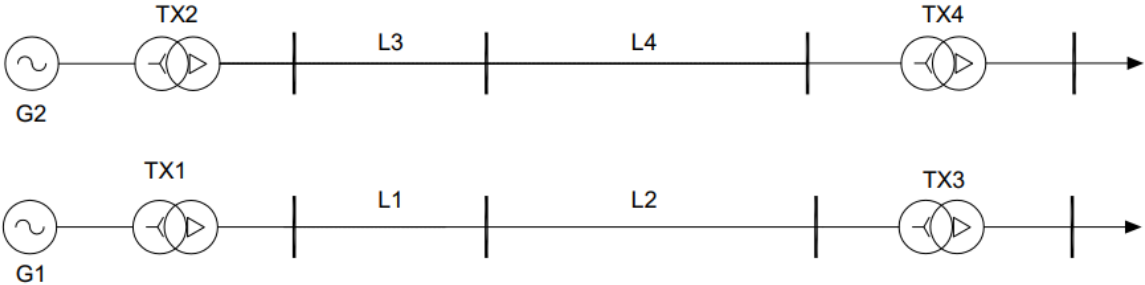


Figure 4.3: Electrical system diagram of Grunnåi Power Plant

The measurements on buses and devices at each point of time in the power transmission system are not included in this thesis since no information from Skagerak Kraft AS was available.

5 Software

Software comprise the entire set of programs, procedures, and routines that helps users to operate the computer system to execute different tasks. Modelling and simulations are mainly based on software with different programming and modelling languages. The modelling language Modelica, the programming language Python and the software Dymola are used in this thesis to model and simulate the hydropower plant. More about the Modelica, Python and Dymola with its library are given in this chapter.

5.1 Modelica

The Modelica language is a language for modelling of cyber-physical systems, supporting acausal connection of components governed by mathematical equations to facilitate large complex systems as electrical, mechanical, thermal, etc [50]. Modelica contains the open source Modelica libraries with about 1600 model components and 1350 functions from many domains. Modelica simulation environment can be available in various software such as CATIA Systems, Dymola, OpenModelica, etc. Industry is using the Modelica language and Modelica libraries for modelling and simulating, also the power plant providers, such as ABB, EDF, Siemens use Modelica to develop their products [50].

5.2 Python

Python is an interpreted, object-oriented, high-level programming language with dynamic semantics. Python supports modules and packages, which encourages program modularity and code reuse. The Python interpreter and the extensive standard library are available in source or binary form without charge for all major platforms, and can be freely distributed. [51]

5.3 Dymola

Dymola, Dynamic Modelling Laboratory, is a complex tool for modelling and simulation of integrated and complex systems for use within automotive, aerospace, robotics, process and other applications. [52]

According to [52], Dymola has the key advantages as follows:

- Compatible model libraries for multi- engineering fields enable high-fidelity modeling of complex integrated systems.
- Modelica-base software, a powerful, object-oriented and formally defined modelling language.
- User can easily build own or adapt existing components to match unique needs. Comprehensive portfolio of model libraries.
- Acausal, equation-oriented models allow a component to be used in different contexts and a model to be used for different studies.
- Relieves the user from converting equations to assignment statements or block diagrams. Simulations are more efficient and robust.
- Provide the real-time simulation on dSPACE and xPC.
- Powerful interoperability options with full FMI support and interfaces to Python, the SIMULIA tools Abaqus and iSight as well as Simulink.
- Provide real-time 3D animation and import of CAD files for visualization.

5.4 OpenHPL

OpenHPL is an open-source hydropower library that consists of hydropower unit models and is modelled using Modelica [50] and is available at [53]. This library is used to model hydropower systems of different complexity and connect them with models from other libraries, e.g., with models of the power system or other power generating sources. OpenHPL also contains examples, waterway components, electromechanical equipment, etc that can be shown in Figure 5.1. Noted that for the model of waterway of Grunnåi hydropower plant, OpenHPL version 1.5.0 is used.

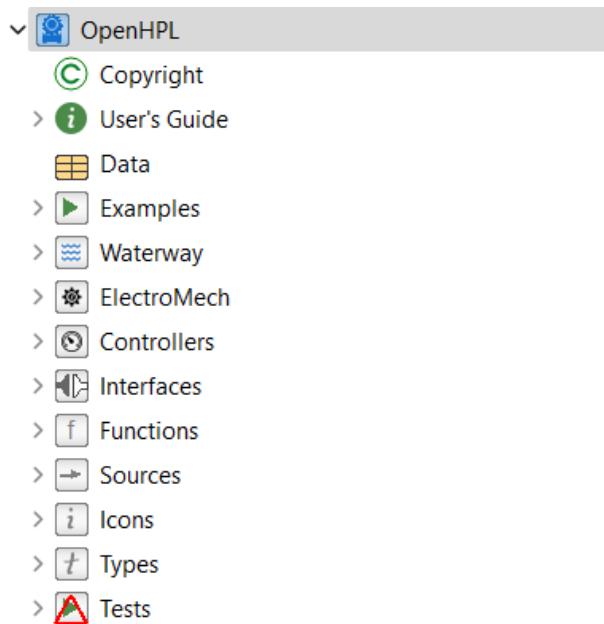


Figure 5.1: Screenshot of OpenHPL

5.5 OpenIPSL

OpenIPSL is open-instance power system library, a library of power system components models written in the Modelica language that can be used for power system dynamic analysis, such as phasor time-domain simulations [54] and is available at [55]. The purposes of OpenIPSL are to be used for research and education to provide as many as possible typical test networks for researching and teaching. The library provides examples, electrical and non-electrical components as can be shown in Figure 5.2.

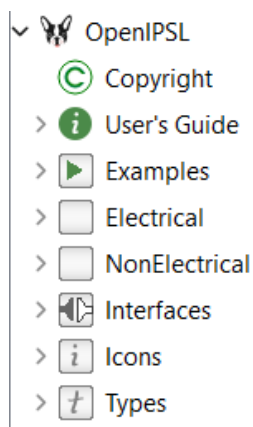


Figure 5.2: Screenshot of OpenIPSL

6 Previous Work

During the fall 2021, the simulation model of Grunnåi hydropower plant was created based on OpenHPL and OpenIPSL in Dymola/Modelica according to the provided information of the power plant in Table 4.1 and Figure 4.2 [4]. There are two simulation models including hydraulic system and electrical system.

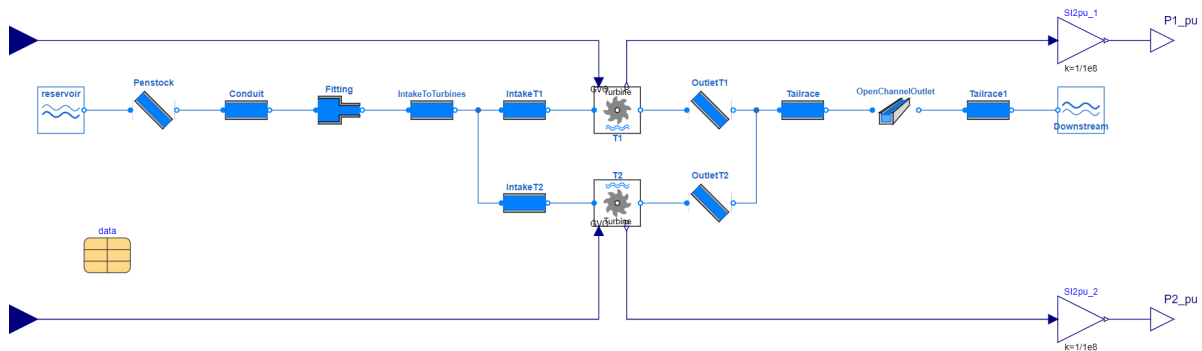


Figure 6.1: Previous work - Simulation model of hydraulic system

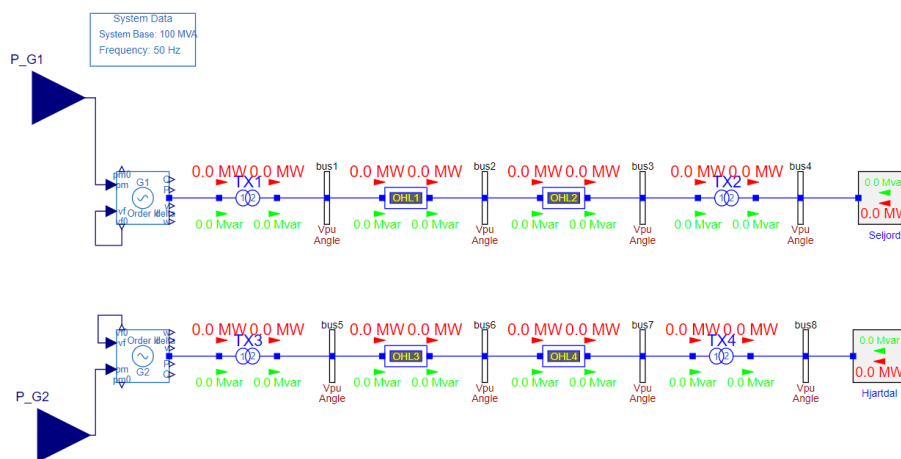


Figure 6.2: Previous work - Simulation model of electrical system

The information of components in simulation models was given in [4]. It is noted that

according to the objective of experiments, the name of each components in the simulation model can be changed in later experiments due to the Table 4.1.

The group decided to take experiments on entire simulation model, first was the hydraulic system model. According to provided data from previous work, there were two input variables in this experiments. First was the average of measured opening value of 5 nozzles of T1 since there is only one input signal of nozzle opening value to turbine block and second was efficiency value from T1 hydraulic efficiency curve, which was generated by peak values of 5 curves shown in Appendix D. T1 generated power was the response of experiment and experimental results was compared with the measurement data. To gain clearly understanding of this experiment, the used dataset of this experiment can be plotted in Figure 6.3. The experimental results were collected and plotted in Figure 6.4.

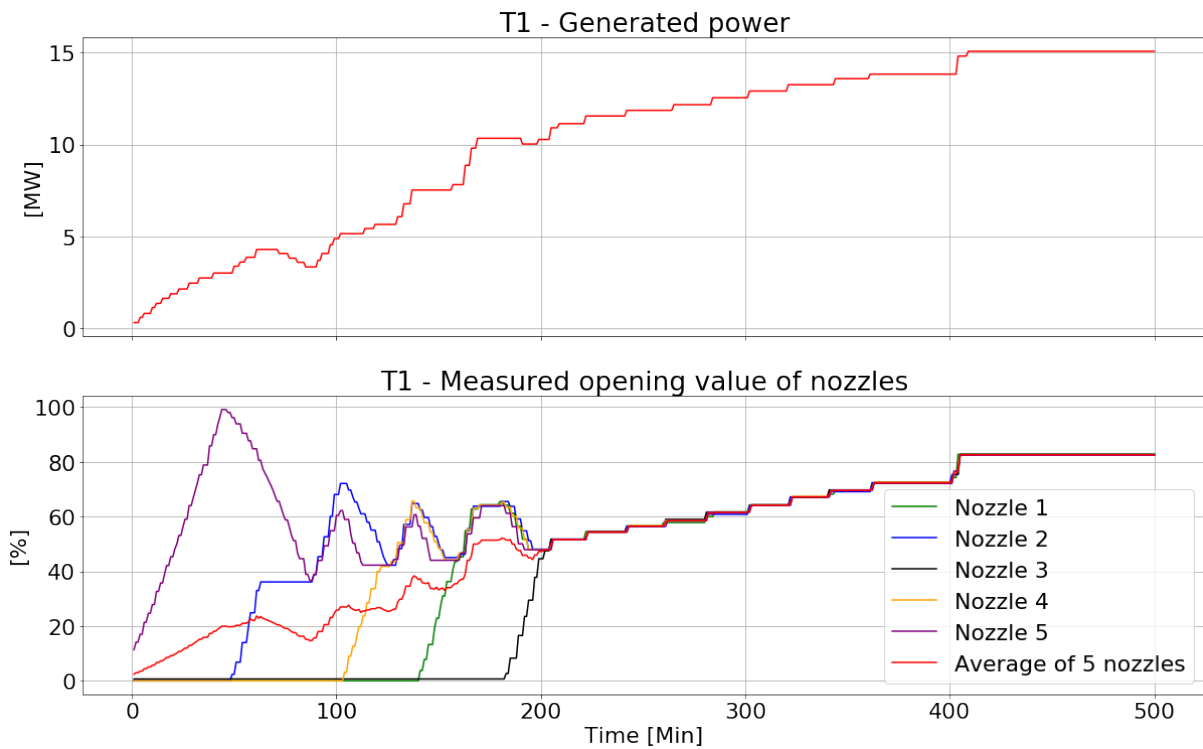


Figure 6.3: Measurement data used in previous work experiment

As can be seen from Figure 6.4, there is large difference between simulation and measurement results, therefore, it is necessary to verify the hydraulic system model before performing experiments on electrical system model.

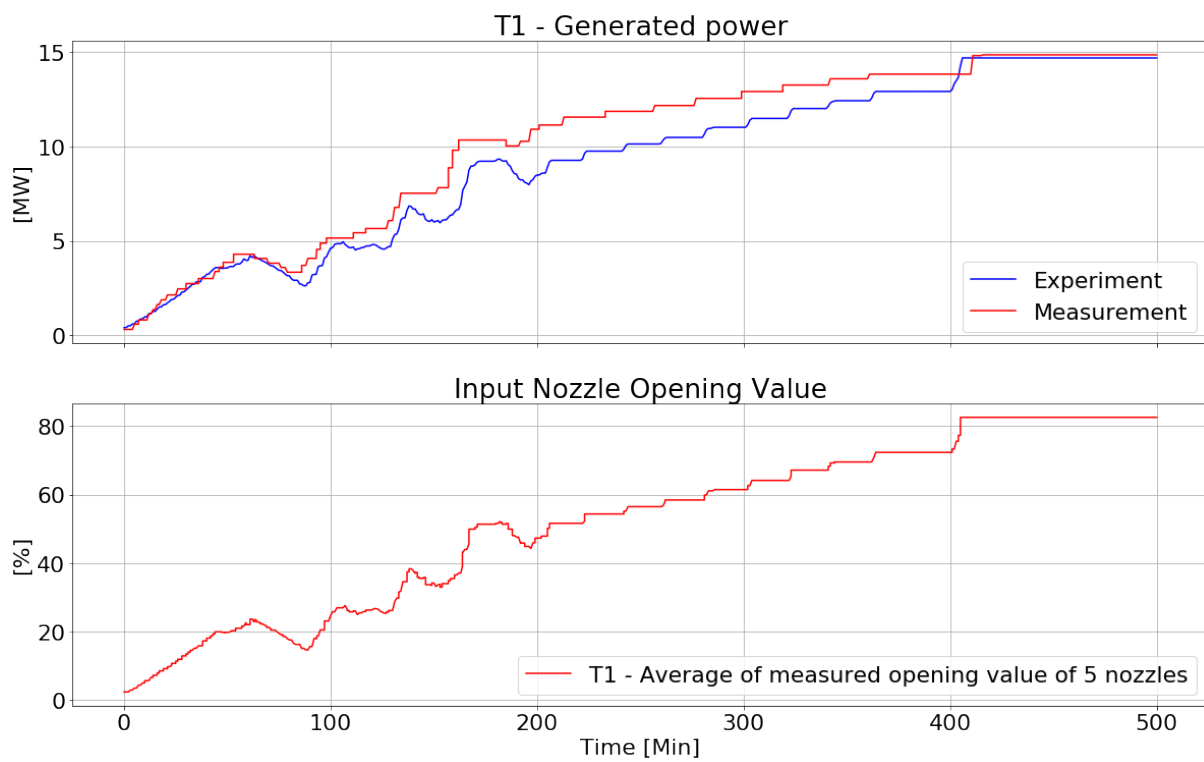


Figure 6.4: Previous work - Comparison of experiment and measurement values

7 Methods

This chapter describes the ways of applying DoE method to simulation model verification and then, the plan of experiments will be conducted. Simulation components used in experiments are also introduced in this chapter.

7.1 DoE Principles

DoE has three basic principles (see Section 2.2). These principles are applied to the hydroelectric plant model verification.

7.1.1 Blocking

The blocking principle is an important method in verifying the hydroelectric power plant model, which is the main goal of the thesis. Therefore, using this approach to the model is the priority work. Blocking is to separate the entire experimental model into groups or blocks for the purpose of verifying each individual. Due to this principle, the model will be divided into main parts that will be verified individually corresponding to associated experiments. During the verification process, the design of each of these parts is optimized with the target of achieving simulation results that are closest to the reference values.

According to the structure of hydropower plant, there are two main systems, hydraulic system and electrical system. In hydraulic system, blocking principle divides the simulation model to three main parts, inlet part, turbines part and the outlet part. Within these main sections, it is possible to divide into other sub-sections whose main purpose is to verify each element in the hydraulic system model.

7.1.2 Replication

With the hydropower plant model experiments, this principle is applied to iteratively the divided parts according to the blocking principle under different operating scenarios of the hydropower plant, to gain the experimental error estimation as well as confirm to give the final conclusion of experiments.

This principle is used when there is a large amount of data available for experiments. For experiments on the simulation models, this method is mainly to confirm the experimental results according to available data from measurement in Table 4.4.

7.1.3 Randomization

The principle, randomization, is applied for hydroelectric plant simulation model for the purpose of model optimization in a situation where it is difficult to select suitable design elements or suitable parameters for components in simulation model. In case that the using simulation library has many elements, randomly use the elements in this library and perform experiments to get the suitable choice so that the results come out as accurate as possible. Similar with case of no information about parameters in components, the parameters for these components are selected randomly.

7.2 Uncontrollable factor

In the simulation model of hydropower plant built by OpenHPL, the required parameters for settings of each units in the model can be found in [4]. These parameters are mostly based on the provided geometry data such as length, slope, etc. However, the uncertain parameter is a parameter with no information as roughness factor of tunnels or conduits in hydraulic system of hydropower plant. That is the uncontrollable variable of the model which is difficult to measure and improve. This factor influences will be focused so the elements containing this parameter are experimented in order to identify its impacts to the experimental results.

7.3 Sequence of Experiments

The verification experiments of hydropower plant model have sequence and cause-and-effect relationship. This means that the results of the previous group of model will directly affect the next group of models. Therefore, setting up the experimental sequence plays an important role in the verification of entire simulation model.

There are two simulation models corresponding with two systems of hydropower plant, hydraulic system model and electrical system model as initial creation from previous work that can be shown in Figure 6.1 and Figure 6.2. Since the electrical system includes the generator units connected with turbine by a shaft that utilizes the generated power of hydraulic turbines to convert into electricity, hence, the hydraulic system model needs to be verified firstly according to the influence of hydraulic system to electrical system.

7.3.1 Planning Experiments of Hydraulic System Model

The hydraulic system includes three main system, inlet system, turbine system and outlet system (see Section 3.1). Based on this structure, the model can be divided into three parts. In addition, in order to have a suitable experimental sequence, it is necessary to consider the relationships between the main parts of the model. According to Equation (3.5) and Equation (3.6), the relationship between inlet system and turbines system can be illustrated. The generated power at the runner of turbines depends on the value of the flowrate into turbines. Therefore, the first performed verification experiments will be conducted on the inlet section to ensure the accuracy of the flowrate into turbines and the parameter settings of the elements in the inlet system. Secondly, the verification of experiments will be conducted at the next part, turbines section and finally is the outlet system. The planned sequence of experiment can be illustrated in Figure 7.1.

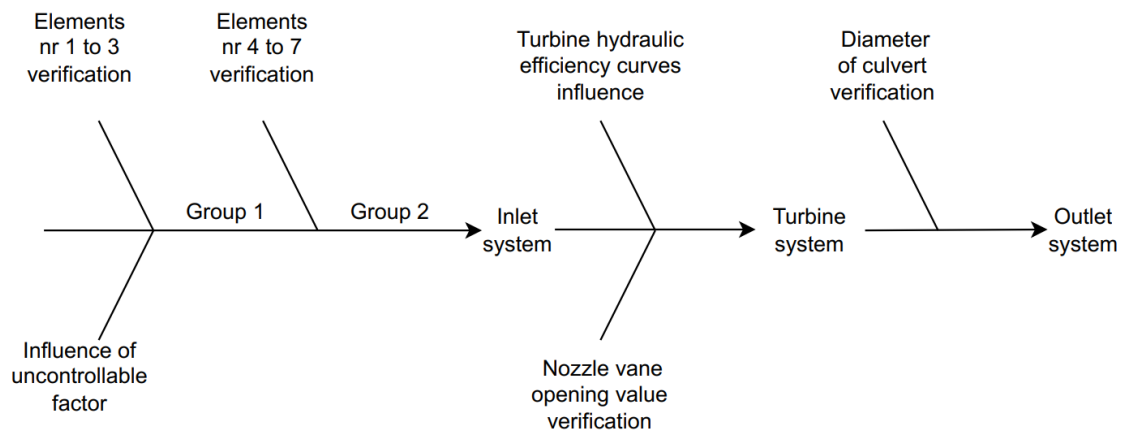


Figure 7.1: Planned sequence of experiments of hydraulic system model

It is noted that Figure 7.1 shows sequence of experiments on each parts of hydraulic system only, so the number of experiments and name of experiments can be optionally changed to accomplish the planned objectives.

Inlet system experiments

The inlet system of the hydraulic model is from the reservoir to conduits into turbines (elements number 1 to 7 due to Table 4.1). However, the waterway from reservoir flowing into the power house is separated into two different ways. Therefore, based on the available data from Table 4.4, it can be divided into two groups:

- Group 1: the elements from reservoir to branch (Element number 1 to 3 in Table 4.1, Tunnel_1, Tunnel_2 and Conduit).

- Group 2: the elements from branch to the conduits into turbines (Element number 4 to 7 in Table 4.1, IntakeT1_1, IntakeT1_2, IntakeT2_1 and IntakeT2_2).

The elements of these two groups are continuously connected to each other, so elements of group 1 in inlet system model is verified first. After verifying, the elements of group 1 model will be used to verify the elements of group 2. These experiments will focus to verify and optimize the inlet system model as well as the influence of uncontrollable factor to the model.

Turbine system experiments

The model of inlet system was verified, therefore the inlet system model will be hold for the next experiments of turbine system model. The turbine parameters in model are set based on the provided information due to Table 4.2. Therefore, there are two factors that need to be verified as hydraulic efficiency and nozzle vane opening value. The turbine experiments will focus to these factors.

Outlet system experiments

The experiments is to verify the elements in outlet system and examine the effectiveness of the drainage system. The elements of this model is elements from number 8 to 11 in Table 4.1, OutletT1, OutletT2, Tunnel_3 and Culvert.

7.3.2 Planning Experiments of Electrical System Model

The electrical system of Grunnâi power plant consists of two branches of G1 and G2 that are independent with each other and have the same structure. It is, therefore, sufficient to conduct experiments on one branch to verify the simulation model of the power system. The challenge is no available measurement data for the verification experiments. Therefore, instead of using measurements, the calculation based on power system analysis theory will be performed and the results of calculation is compared with the simulation results.

In electrical system, generator is connected turbine by a shaft and converts the mechanical power to electric power. However, since the lack of measurement data in electrical system, the experiments on this system are mainly focus to simulation elements in this system. In the experiment, the voltage drop across transmission system is considered. An experiment can be setup by changing the load values and with the available parameters on transmission systems, the voltage drop can be calculated. This calculation results will be compared with experimental results.

7.4 Components for Experiments

Simulation model experiments are conducted totally in Dymola/Modelica, therefore, getting clearly understanding about Modelica simulation is important. In addition, to setup experiments for simulation model, there are several new block components built based on Dymola/Modelica.

7.4.1 Flowrate Sensor Block

In this work, a flowrate sensor block is built with the purpose of measuring the flowrate into the turbine and outputting a numerical value. Figure 7.2 shows the symbol of flowrate sensor block used in experiments.

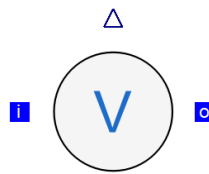


Figure 7.2: Symbol of flowrate sensor block

This block is based on Equation (7.1). It has two inputs and one output. Two inputs are for connecting to water pipes or direct connection to turbine block. Output is the numerical value of flowrate passing through this block. In simulation experiments, this sensor block will automatically output the value of flowrate into turbine through the output port, and this value is used to find the corresponding hydraulic efficiency value. It is noted that the inputs of this block have two ports named i and o, so the positions of two ports must be placed in the correct position corresponding to the direction of the flow from i to o in order to get the correct output value.

$$Q_i = Q_o \quad (7.1)$$

Where:

Q_i - Inlet flowrate [m^3/s]

Q_o - Outlet flowrate [m^3/s]

7.4.2 Hydraulic Efficiency Block

The hydraulic efficiency block is created and applied in experiments. This block is created by available mathematical domain in Dymola. Based on the manufacture’s information as shown in Appendix D with T1 and T2 hydraulic efficiency curves, the hydraulic efficiency value can be gained due to flowrate into turbine. However, instead of only one efficiency curve for turbine, there are several efficiency curves in different operating state.



Figure 7.3: Symbol of T1 and T2 hydraulic efficiency block

These blocks have one input and one output. The input is the value of flowrate into turbine that is taken from flowrate sensor block and the output is the corresponding efficiency value according to efficiency curves.

Internal part of T1 hydraulic efficiency block contains five tables corresponding to five efficiency curves and T2 hydraulic efficiency block consists of one table as one efficiency curve. The hydraulic efficiency curves retrieved from these blocks can be shown in Appendix D. In experiments, the input of this block is the output signal from flowrate sensor block.

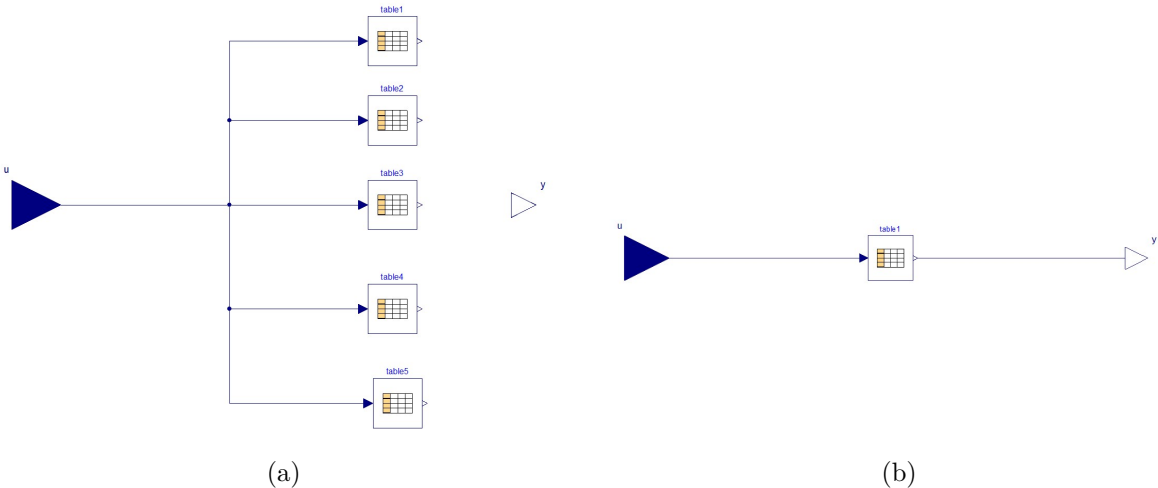


Figure 7.4: (a), (b) Internal part of T1, T2 hydraulic efficiency block, respectively

7.4.3 Nozzle Opening Block

This is a block built to calculate the value of nozzle opening value into turbine based on generated power of turbine. Inside this block, there is the connected mathematical blocks showing the relationship between the input and output. The nozzle opening block of T1 is named 'Uv_T1' and for T2 is 'Uv_T2'. Internal part of these blocks can be shown in Figure 7.6.



Figure 7.5: Symbol of nozzle opening block

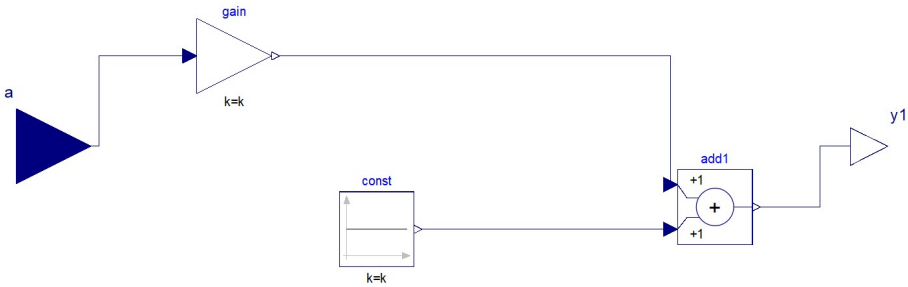
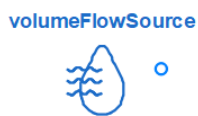


Figure 7.6: Internal part of nozzle opening block

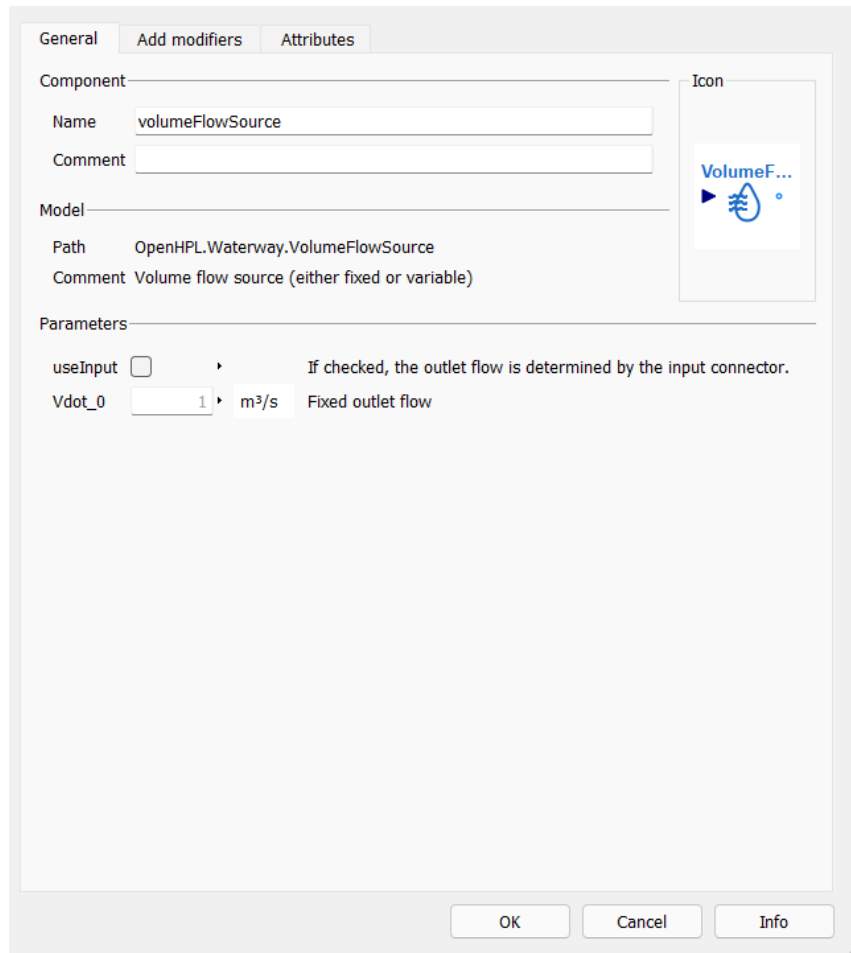
7.4.4 Volume Flow Source Block

Performing experiments on each portion of the simulation model, it requires a component representing the connection point between the parts of the model. In experiments, this block is used to replace the point of branching or turbines.

This block has one output that is the water flowrate, used to connect the other hydraulic components. The value of water flowrate will be setup in the setting box of this block if the value is constant as can see in Figure 7.7. In the situation of the varied value of flowrate, the box named 'useInput' will be ticked to use the signal of varied value.



(a)



(b)

Figure 7.7: (a), (b) Symbol and setting window of volume flow source block, respectively

7.4.5 Turbine Block

Turbine block used in experiment is inherited from turbine version of OpenHPL. This new version turbine has one change comparing with the initial version. The hydraulic efficiency, instead of placing in the setting box, it will be placed as the input terminal since there are several hydraulic efficiency curves instead of one curve in the initial version. Therefore, this turbine block will have one more input port as the initial version as shown in Figure 7.8 comparing with Figure 7.9. This change helps turbine block use different efficiency curves in the different operating condition.

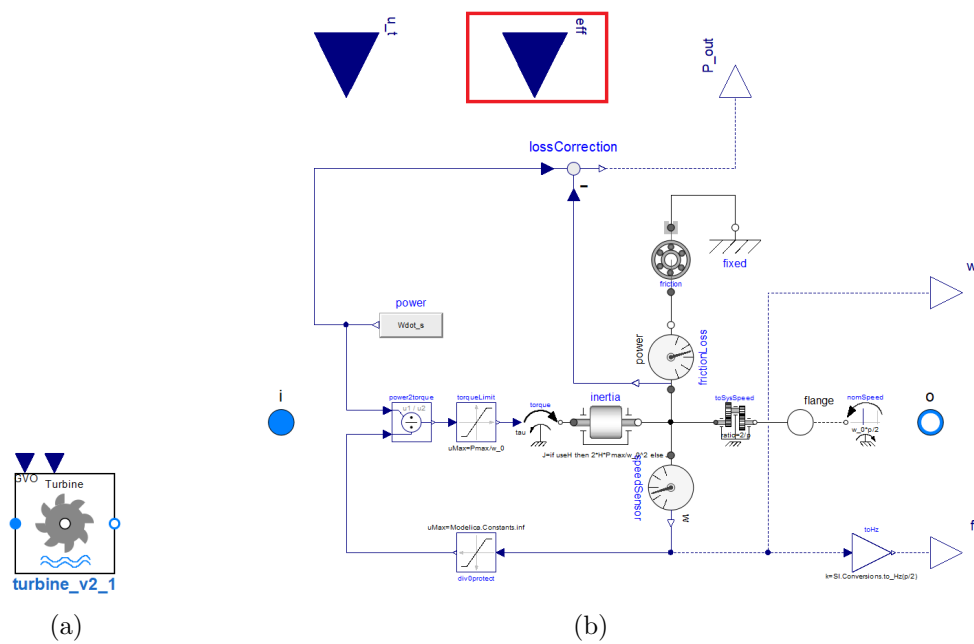


Figure 7.8: (a), (b) Symbol and internal part of new version turbine block with new efficiency port framed in red, respectively

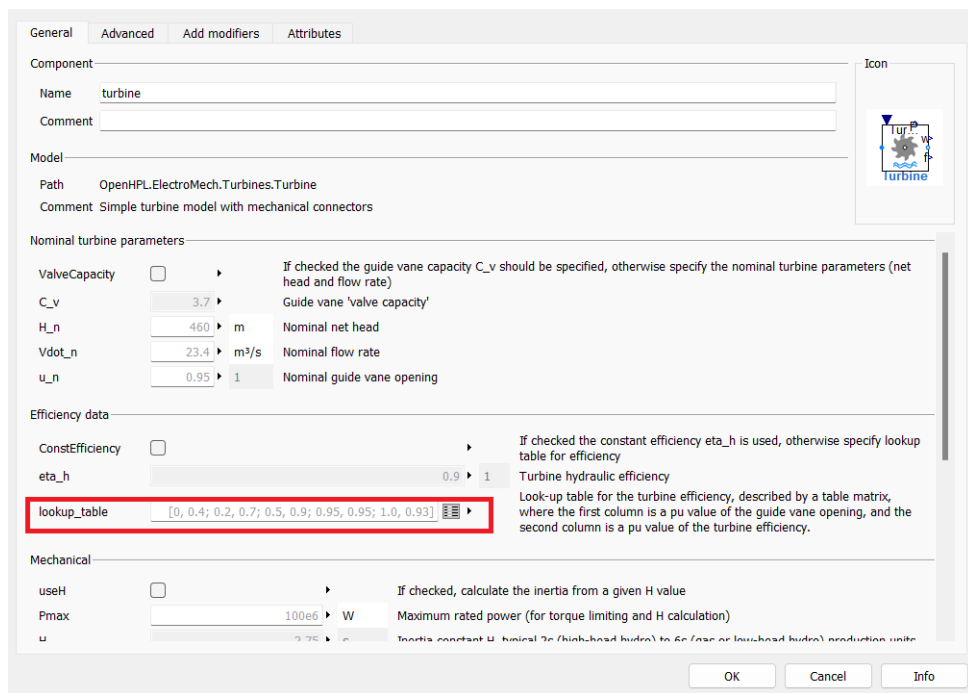


Figure 7.9: Hydraulic efficiency in window settings framed in red of original turbine block of OpenHPL

7.5 Linear Regression

Linear regression shows the relationship of response based on several variables (see Section 2.5.1). Python is very useful to implement linear regression. There is a widely used package in Python library is scikit-learn [56] that is used to implement regression, classify, cluster or more. This is the open-source package. There are four basis steps to implement linear regression using this package [57]:

- Step 1: Import the packages.
- Step 2: Provide data to work.
- Step 3: Create a regression model and fit it with existing data.
- Step 4: Check the results of model fitting to know whether the model is satisfactory.

The data to create linear regression model in this package comes from the simulation results from the hydropower plant model. Based on these results, the equation of linear regression model can be created. The parameters of the equation are used to build nozzle opening block.

7.6 Data Acquisition and Preparation

In chapter 6, previous work is used detailed and clean dataset provided from Skagerak Kraft AS company. However, with new data provided, it is necessary to gain data processing and cleaning before experiments implementation.

7.6.1 Data Format

The provided data is in CSV (comma-Separated Values) format, a typical file format used to store measurement values from sensors. CSV files is a plain text file that consists of a list of data, which allows for exchange or transport of data between different programs.

Grunnåi hydroelectric power plant uses two main data sources from monitoring systems, HydroCord and SCADA. The measurement values of sensors are transported and stored in both these data sources. In the CSV files, the data is divided into six separated columns, "unitName", "measurementName", "datasource", "engineeringUnit", "timestamp" and "value". The column "unitName" illustrates the components in hydropower plant such as turbines, generators, etc. while the column "measurementName" contains the name of the measured quantities such as flowrate, active power, etc. There are about hundreds of measured quantities in this column. Each of these quantities has a different recorded time such as active power has every 4 sec recorded time or 5 sec for flowrate, and the

output time is recorded in the column “timestamp”. The column “timestamp” is in ISO 8601 format, an international standard data and time [58].

7.6.2 Data Processing

This work is processing data from provided measurement data from Skagerak company. CSV files supports transporting and storing data, but are not visualized and difficult to work with data. Thus, Pandas package [59] in Python is applied, which provides fast, flexible way to analyze data. It is a powerful tool to explore dataset including CSV files. Pandas will extract the data from that CSV files into a DataFrame – a table and retrieving data becomes simpler based on the commands available in Python.

The procedure for formatting and processing data from CSV files can be describes in four steps where the original data is implemented into Python for analysis until the complete dataset with necessary data for experiments.

- Step 1: Using Pandas package in Python to import CSV files. Data, currently, can be read directly in Python commands.
- Step 2: The column ‘timestamp’ of CSV files needs to convert format from ISO 8601, which is not supported by Python, to another format. Using localize function provided by Python library that is useful to treat particular time zone format.
- Step 3: Filter the needed data for the experiments. These data is estimated in minutes instead of seconds like CSV files. Data in minutes is output based on the average value obtained for one minute.
- Step 4: The data required for experiments after filtering are stored in a new database and exported by pandas package to new CSV dataset applying for experiments.

This procedure supports visualizing and analyzing easily millions data points for model experiments.

It is noted that because of different recorded time of each quantities, in a specified period of time, there appears NaN values (missing values) from other signals that leads to data cleaning requirement and these NaN values have to be dropped.

7.7 DoE Steps

7.7.1 Selection of Experimental Design

This stage is step 5 in DoE steps as mentioned in Section 2.4.5 that is used to select suitable experimental design for experiments. This step is extremely helpful for real-world

experiments in case of having large amount of variables with different levels. The right selection of experimental design can help perform experiment more simple and avoid wasting time and experiment materials since the number of experiment runs can be calculated based on objectives, process variables with their levels and responses of the experiment.

For experiments on simulation model, the process variables are changed over simulation time. This means that the variables have different levels corresponding with the point of simulation time. Therefore, the experimental design is applied for entire experiments on hydropower plant model that is OFAT and this step is not mentioned in these experiments.

7.7.2 Interpreting Experimental Results

As the step 7, interpreting experimental results, in DoE steps (see Section 2.4.7), some techniques are used to express the experimental results. There are two techniques used, graphical representation and mean absolute percent error calculation.

Graphical Representation

In experiments, the results from the experiments are plotted and compared with the corresponding measurement data to examine the difference of two values based on these graphs. There are many types of comparison graphs, such as column, bar, pie or line. However, the measurement data used as inputs and outputs of hydropower plant simulation model shown in Table 4.4 are variables that change over time, thus, line graph is suitable option which can reveal trends or process over time.

Mean Absolute Percentage Error (MAPE)

Mean Absolute Percentage Error (MAPE) is the mean or average of the absolute percent error. MAPE is used to know how accurate a model is. This method defines the accuracy as a percentage, and the lower MAPE means that the experimental results is closer to the reference value or has the lower difference. According to [60], the interpretation of MAPE is defined as:

$$MAPE = \frac{1}{n} \sum_{t=1}^n \left| \frac{A_t - F_t}{A_t} \right| \quad (7.2)$$

Where:

n - Number of fitted points

A_t - Actual/Measurement value

F_t - Experiment/Simulation value

t - Point number

With a large amount of simulation results and measurement data, Python is applied to the MAPE calculation. Experimental results are imported to Python and then, using Python commands to calculate quickly the MAPE value.

7.7.3 Evaluation Recognition

Using MAPE to compare simulation results with measurement data, a MAPE less than 5% is considered as an indication that the simulation result is acceptably accurate [61]. Therefore, in some experiments, the acceptance evaluation criteria is difference between experimental and actual values lower than 5%.

8 Experiments

These set of experiments are performed as the objective of the thesis that is verification and optimization of the simulation model. The sequence of experiments is performed with the first performed experiments of hydraulic system including inlet system, turbine system and outlet system that can be shown in Figure 8.1 and lastly is electrical system.

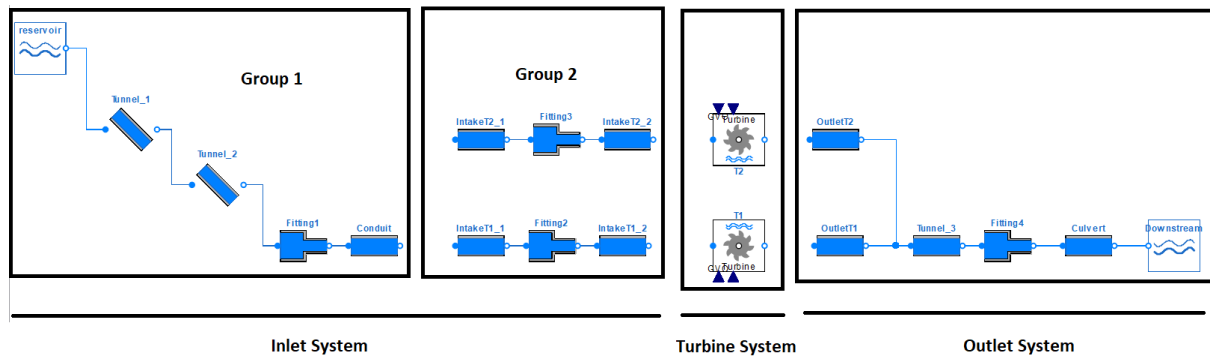


Figure 8.1: Hydraulic system model with three main parts

8.1 Inlet System Experiments

In the inlet system model experiments, there are experiments on two groups, group 1 and group 2 (see Section 7.3.1).

- Group 1: the elements from reservoir to branch (Element number 1 to 3 in Table 4.1, Tunnel_1, Tunnel_2 and Conduit)
- Group 2: the elements from branch to the conduits into turbines (Element number 4 to 7 in Table 4.1, IntakeT1_1, IntakeT1_2, IntakeT2_1 and IntakeT2_2)

8.1.1 Group 1 Experiments

Experiment 1 - Verify group 1 elements

Objectives recognition The objective of experiment is to verify the group 1 elements, Tunnel_1, Tunnel_2 and Conduit, in inlet system model.

Selection of response The response of interest for the experiment is the water pressure at Conduit element.

Selection of process variables The variable of this experiment is the measurement values of flowrate at Conduit element.

Evaluation criteria recognition The evaluation criteria of this experiment can be done by the comparison of experimental results and measurement data. Two results are plotted and MAPE is calculated. Similar graphics visualization of two results and $MAPE < 5\%$ are accepted.

Performing the experiment The simulation model of this experiment that is elements of group 1, is set up as Figure 8.2. The parameters of these elements are according to the geometry data of the inlet system, element number 1 to 3 as shown in Table 4.1, Tunnel_1, Tunnel_2 and Conduit. Block named “Data” contains the measurement values of pressure and flowrate at Conduit element. The input of block “Volume flow source” named “Branch” is measurement data of flowrate at Conduit element.

The roughness factor of Tunnel_1, Tunnel_2 and Conduit components in this simulation model will set up at zero because of unknown influence of this factor to the entire system and that will be examined in later experiment.

This part of hydraulic system model in previous work is also taken to experiment to consider the accuracy of this part.

Interpreting experimental results The experimental results are collected and plotted in Figure 8.3.

The MAPE of this experiment can be resulted in Table 8.1.

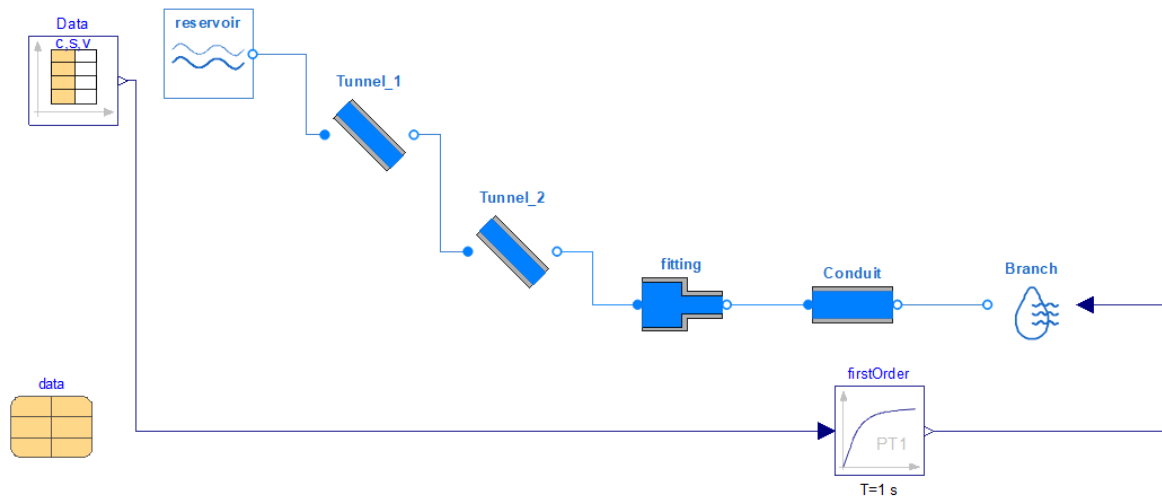


Figure 8.2: Simulation model of experiment 1

Previous work	Experiment 1
0.8%	0.5%

Conclusions and recommendations Figure 8.3 illustrates no large difference between the experimental results and the measurement values. However, with the zoom in observation, there are difference between these results due to the variation of flowrate values.

Generally, the results from experiment 1 and model from previous work have difference comparing with measurement values. Experiment 1 results show less difference than results from model in previous work. Furthermore, MAPE of experiment 1 is lower than previous work model with MAPE 0.5% that demonstrates the less discrepancy between the experimental and measurement values.

The experiment of elements in group 1 model shows that there is almost no error compared to the measured value. Therefore, these elements can be used for later experiments.

Confirmation run To verify again the group 1 elements in inlet system model, the confirmation run can be applied. Using another provided dataset, the confirmation run results can be shown in Figure 8.4. MAPE of this confirmation run is illustrated by Table 8.2.

Through confirmation run, group 1 elements in inlet system model are validated and can be used for later experiments.

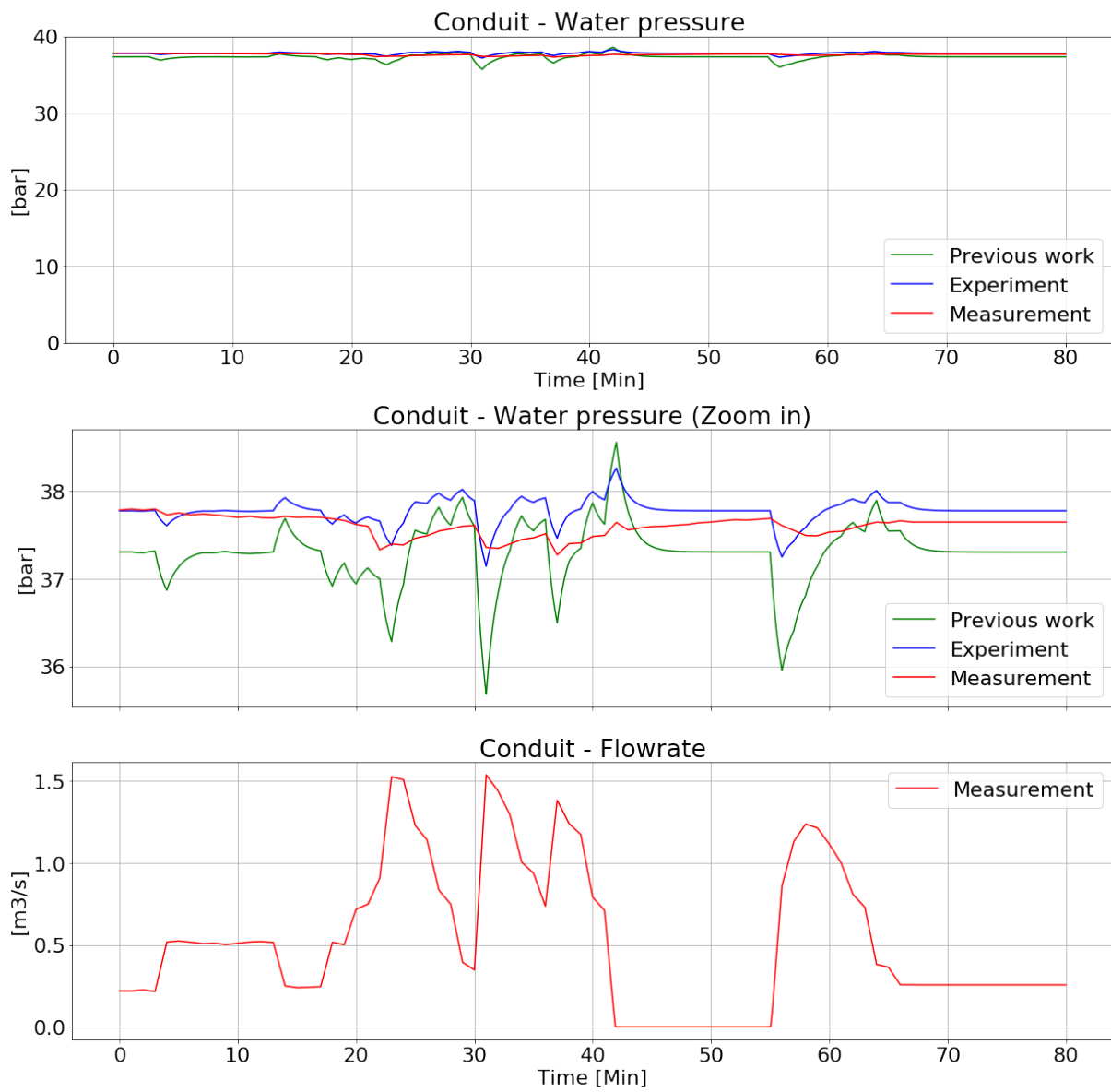


Figure 8.3: Experiment 1 - Comparison of experiment and measurement values

Table 8.2: MAPE of confirmation run of experiment 1

Experiment 1	Previous work
0.07%	1.31%

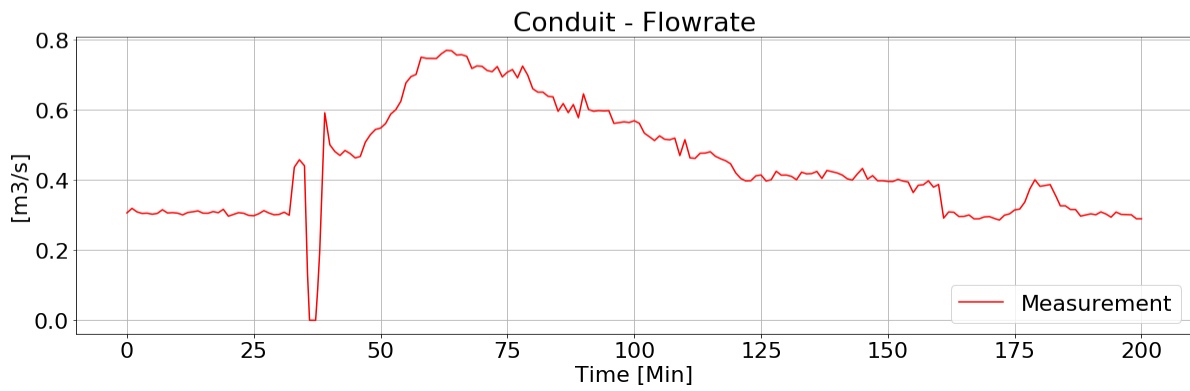
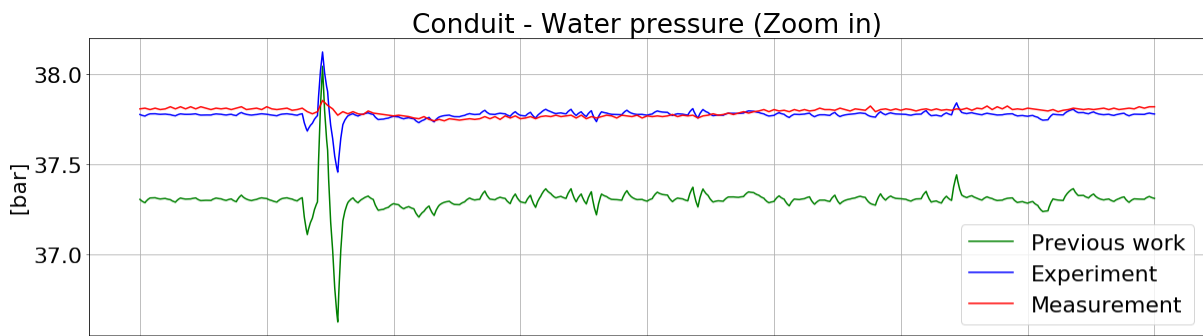
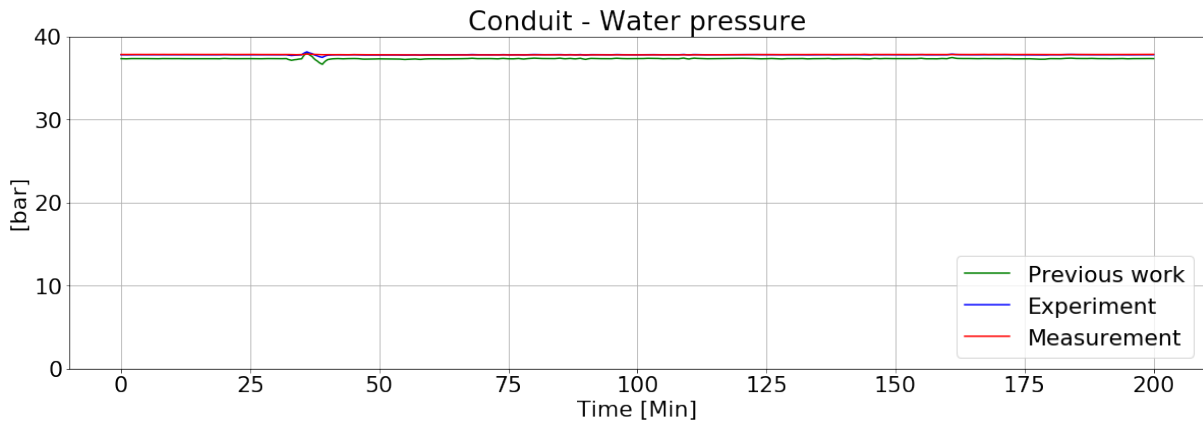


Figure 8.4: Experiment 1 - Confirmation run

Experiment 2 - Roughness factor consideration

Objectives recognition The objective of experiment is to verify the roughness parameter of tunnel and conduit elements and identify its influence to the simulation model.

Description The first experiment on group 1 elements is set up with the roughness parameter of these elements at zero. In reality, the tunnel and conduit always have roughness factor. This experiment is to find the suitable roughness parameter of components in the simulation model and figure out its influence on the experimental response. Furthermore, the roughness factor may be culprit causing the difference between results of experiment 1 and previous work. Therefore, the roughness factor of element units in previous work is taken into this experiment.

The roughness factor of pipe can be determined by the material of pipe. From provided information, the material of pipe in the power plant is steel, therefore, the roughness parameter of pipe unit (Conduit) in the simulation model will be setup at 0.045mm according to Table 3.1. The unknown parameter needed to be determined is roughness factor of tunnel units (Tunnel_1, Tunnel_2) in the model and that is the objective of this experiment.

Selection of response The response of interest for the experiment is the water pressure at Conduit element (same as experiment 1).

Selection of process variables There are two variables in this experiment:

- The values of flowrate at Conduit element (same as experiment 1)
- The values of roughness parameter of tunnel units. The roughness parameter has three levels, low, medium and high with high level is the roughness factor of tunnel units in previous work. Table 8.3 shows the value corresponding to each level.

Table 8.3: Tunnel roughness parameter of each level

Process parameter	Low level	Medium level	High level
Tunnel roughness parameter	0.1m	0.2m	0.3m

Evaluation criteria recognition The evaluation criteria of this experiment is to determine the roughness parameter of tunnel that makes the experimental results have the lowest MAPE. The graph of experiment results can be plotted to observe the difference between levels of parameter.

Performing the experiment The simulation model used for this experiment is same as experiment 1 in Figure 8.2. The roughness parameter of Conduit element is setup according to Table 3.1 with the value, 0.045mm and the roughness parameter of tunnel units is changed according to the levels in Table 8.3. In this experiment, there are two elements containing this parameter that is Tunnel_1 and Tunnel_2.

Interpreting experimental results The experimental results are collected and plotted in Figure 8.5.

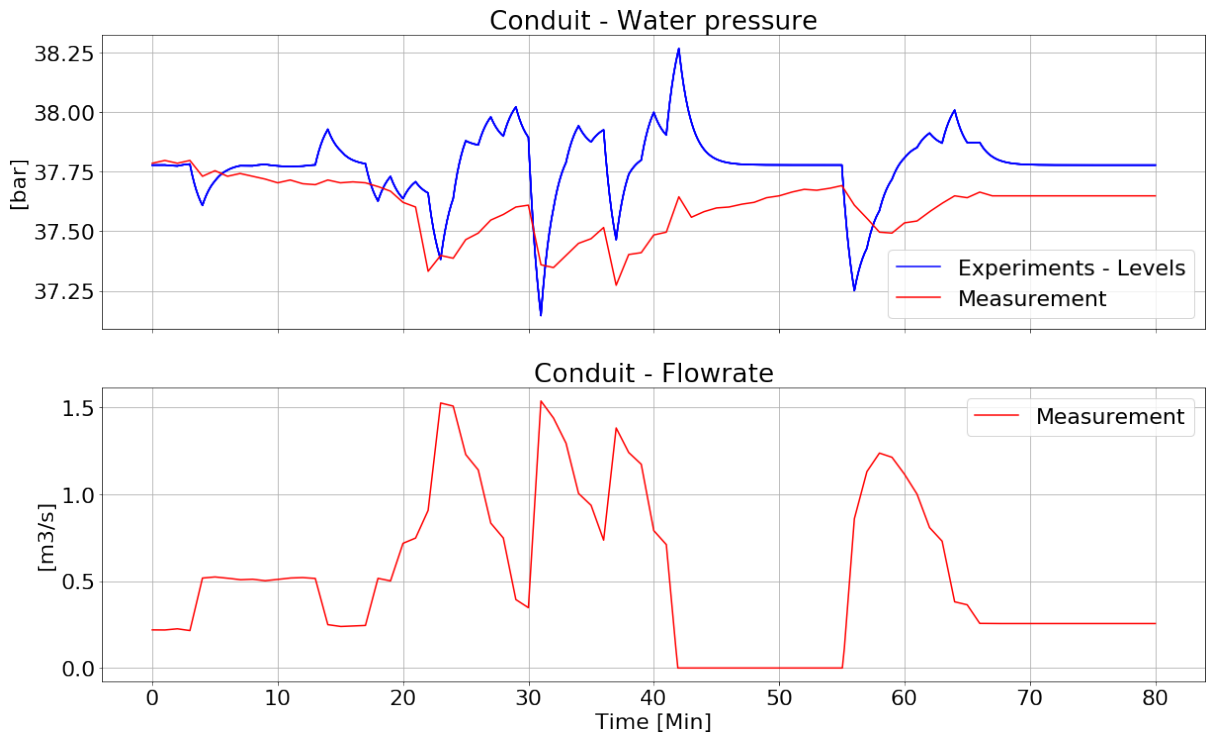


Figure 8.5: Experiment 2 - Comparison of experiment and measurement values

The MAPE of this experiment can be resulted in Table 8.4.

Table 8.4: MAPE of experiment 2

Experiment 1	Low level	Medium level	High level
0.5%	0.5%	0.5%	0.5%

Conclusions and recommendations From Figure 8.5, there is no difference between three level of roughness parameter comparing with the experiment 1 results. According to

Table 8.4 with the same MAPE in each level, it can be concluded that there is no difference between the values corresponding to the change of levels in roughness parameter of tunnel and demonstrates that the roughness parameter of tunnel has no influence to the results of the simulation model and therefore, this factor is not cause of difference between experiment model and previous work model. The experiment model will be hold for next experiments since better simulation results comparing with results from previous work model through experiment 1.

However, in order to simulate properly under practical condition, the roughness parameter of tunnel units in the model will be hold in high level at the value, 0.3m and the pipe units will be hold as 0.045 mm in later experiments.

8.1.2 Group 2 Experiments

The group 1 elements in inlet system model was verified, therefore this model will be used for experiments on group 2 elements. Figure 8.6 shows the verified elements of group 1 and elements of group 2 need to be verified in inlet system model.

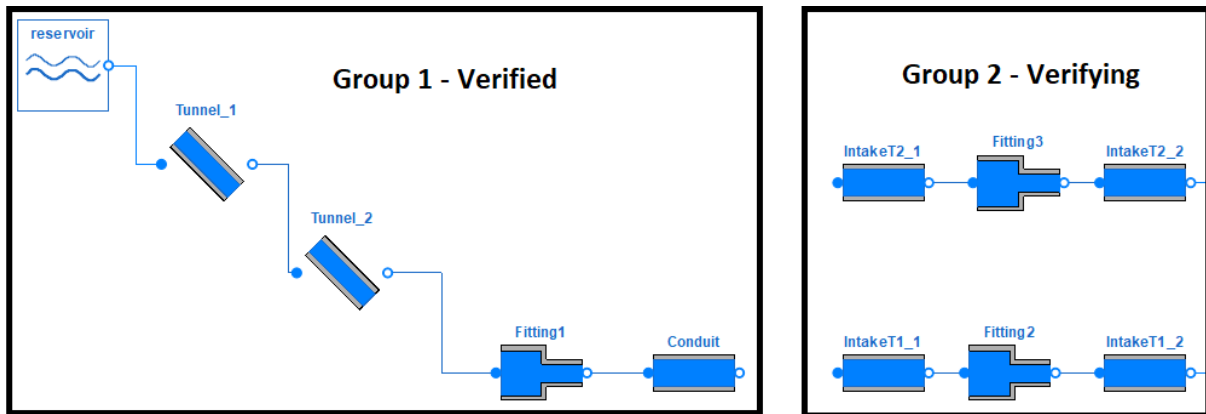


Figure 8.6: Group 1 and group 2 elements in model of inlet system

Experiment 3 - Optimal design of branching part

Objectives recognition The objective of experiment is to determine the optimal design of branching part in inlet system.

Description The elements of group 2 are set up corresponding to the geography parameters in Table 4.1. According to Figure 8.6, it requires the connection between the group 1 and group 2 in the model and illustrates the branching point of two separate waterway flowing into T1 and T2. There are three different branching designs in simulation model to connect the elements between group 1 and group 2:

- Design 1: Using connection same as hydraulic system model of previous work (see Chapter 6).
- Design 2: Using “Fitting” component.
- Design 3: Using “bendPipe” component.

Selection of response The response of interest for the experiment is the water pressure at T2 inlet or IntakeT2_1 element from simulation model.

Selection of process variables There are two variables in this experiment:

- The measurement values of flowrate at IntakeT2_1.
- Three designs of branching part.

Evaluation criteria recognition The evaluation criteria of this experiment is to determine the best design that makes the simulation results have the lowest difference comparing with measured values or lowest MAPE. The graph of experimental results can be plotted to observe the difference between three designs.

Performing the experiment The experiment of design 3 is implemented as Figure 8.7 and another designs, design 1 and design 2 will be implemented similarly. The blocks named “T1” and “T2” are “Volume flow source” block which are used to represent turbines without using turbine models in the experiment since these models have not been verified.

In design 2, the parameter of component “Fitting” representing for the branching point is setup according to the diameter of “Conduit” and “IntakeT1_1” that have the same diameter. In design 3, the parameter of component “bendPipe” is setup according to the diameter of “Conduit” and “IntakeT1_1” and the loss coefficient parameter is set as default, 0.5.

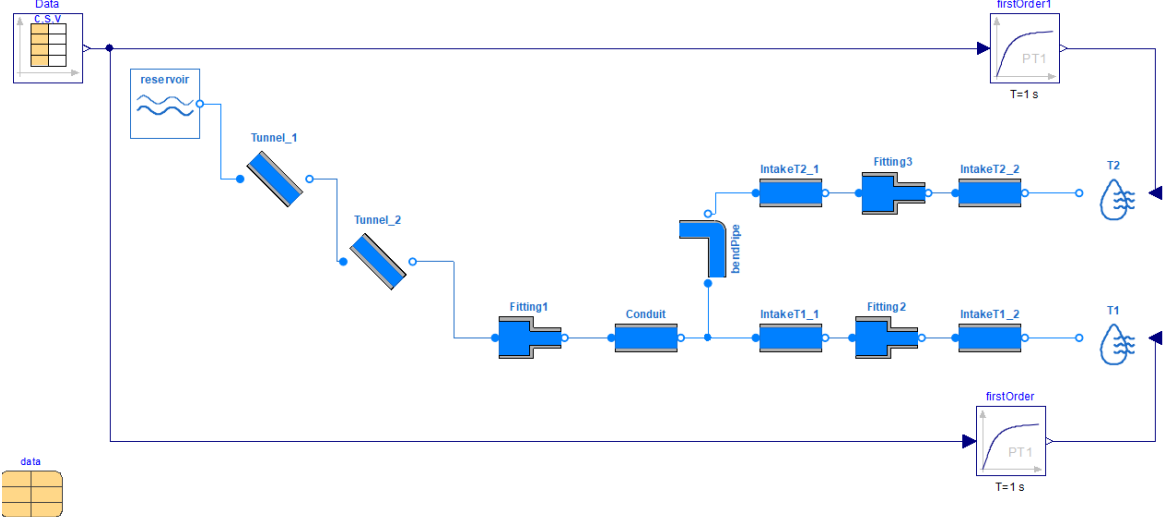


Figure 8.7: Simulation model of design 3 in experiment 3

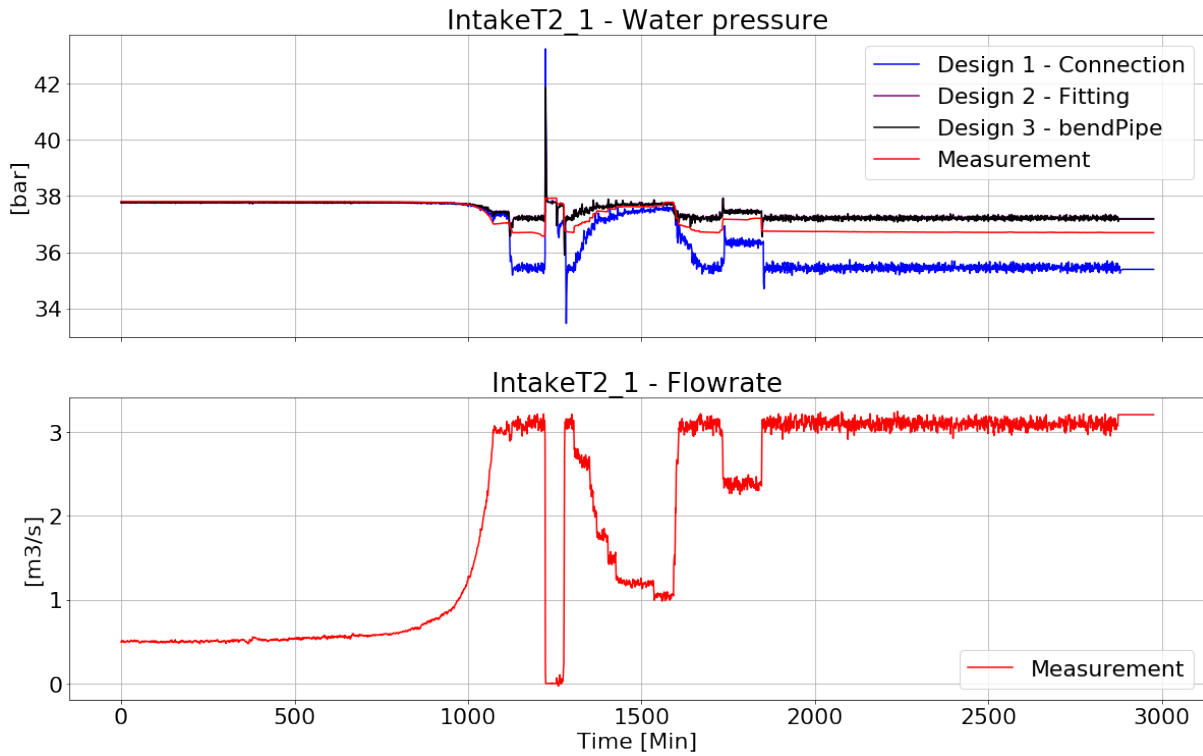


Figure 8.8: Experiment 3 - Comparison of experiment and measurement values

Interpreting experimental results The experimental results are collected and plotted in Figure 8.8.

MAPE of this experiment can be resulted in Table 8.5.

Design 1	Design 2	Design 3
1.82%	0.74%	0.72%

Conclusions and recommendations According to Figure 8.8, from 1000 minutes onwards, comparing with the measurement data, design 1 experimental results shows the most difference in three designs while the design 2 and design 3 give the nearly similar results.

According to Table 8.5, it can be concluded that the design 1 with using basic connection gives the most difference while the design 3 gives the lowest difference comparing with the measurement values. However, the loss coefficient parameter of component “bendPipe” in design 3 is setup as default. This parameter can be experimental to give the better results.

Experiment 4 - Loss coefficient parameter of “bendPipe” component

Objectives recognition The objective of experiment is to determine the optimal loss coefficient parameter of “bendPipe” component.

Description The loss coefficient parameter of “bendPipe” component of design 3 in experiment 3 is setup according to guess or manufacture’s design. Because of no information in this component, this parameter will be chosen randomly as being suitable for the simulation model with the purpose of obtaining the best simulation results.

Selection of response The response of interest for the experiment is the water pressure at T2 inlet or IntakeT2_1 element from simulation model. (same as experiment 3)

Selection of process variables There are two variables in this experiment:

- The value of flowrate at IntakeT2_1 (same as experiment 3)
- Three levels of loss coefficient parameter of “bendPipe” component of design 3 as shown in Table 8.6.

Table 8.6: Loss coefficient parameter of ”bendPipe” component

Process parameter	Low level (Default)	Medium level	High level
Loss coefficient parameter	0.5	5	10

Evaluation criteria recognition The evaluation criteria of this experiment is to determine the best parameter value that makes the simulation results have the lowest difference comparing with measured value or lowest MAPE. The graph of experimental results can be plotted to observe the difference between three levels.

Performing the experiment The experiment is implemented according to Figure 8.7. The loss coefficient parameter of “bendPipe” component will be changed corresponding to each level of each experiment.

Interpreting experimental results The experimental results are collected and plotted in Figure 8.9.

MAPE of this experiment can be resulted in Table 8.7.

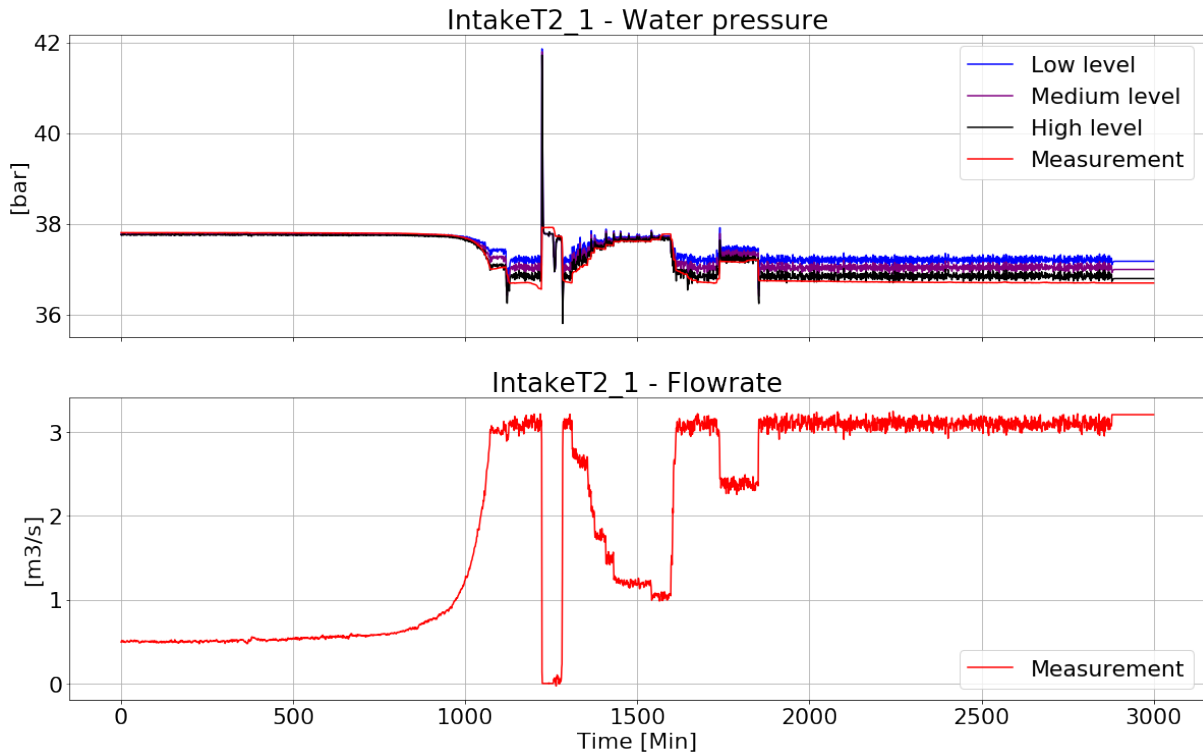


Figure 8.9: Experiment 4 - Comparison of experiment and measurement values

Table 8.7: MAPE of experiment 4

Low level	Medium level	High level
0.72%	0.49%	0.25%

Conclusions and recommendations According to Figure 8.9, from 1000 minutes onwards, the experimental results of high level results shows the most accurate in three levels.

According to Table 8.7, it can be concluded that the loss coefficient parameter of “bend-Pipe” as 10, gives the simulation results the lowest difference comparing with measurement values.

Confirmation run To confirm the optimal design of branching part as component “bend-Pipe” with its loss coefficient parameter as 10, another available dataset is used in confirmation run. The experimental results of confirmation run are collected and plotted in Figure 8.10. Furthermore, MAPE of confirmation run can be resulted in Table 8.8.

MAPE of tuned “bendPipe” component of confirmation run is also low demonstrating the best optimal design of branching part for inlet system model.

Table 8.8: MAPE of confirmation run in experiment 4

Tuned bendPipe	Connection
0.21%	0.90%

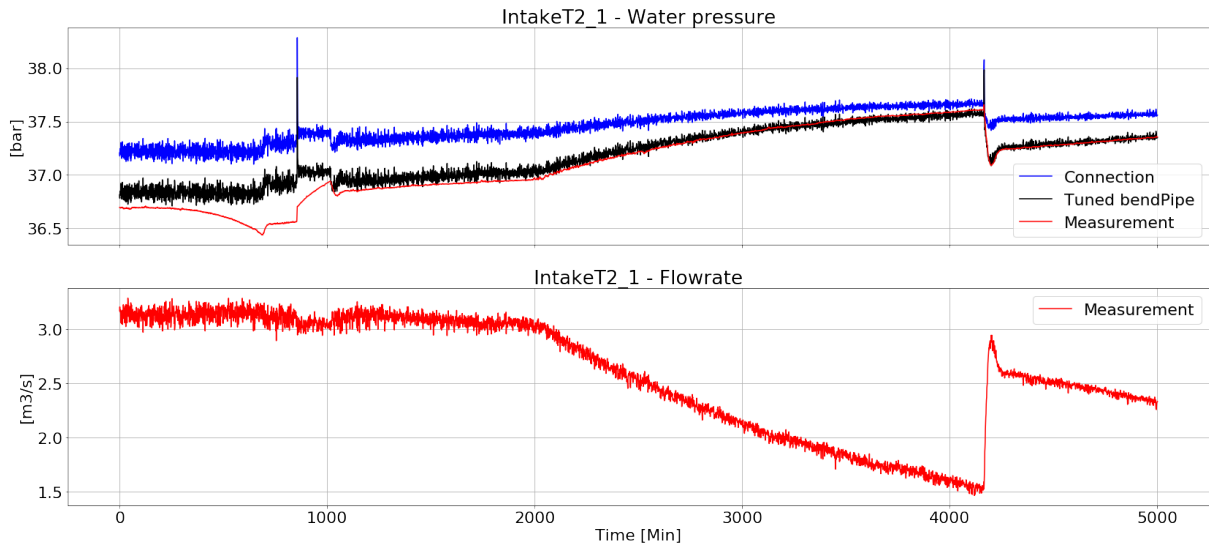


Figure 8.10: Experiment 4 - Confirmation run

Therefore, through experiments of elements of group 1 and group 2, the inlet system of the hydraulic system simulation model are optimized and verified. This inlet system model can be used for later experiments.

8.2 Turbine System Experiments

The set of experiments on turbine system will be performed as Figure 7.1 since the inlet system model was verified. Figure 8.11 illustrates three main parts of hydraulic system simulation, from left to right, verified inlet system, verifying turbine system and not verified outlet system.

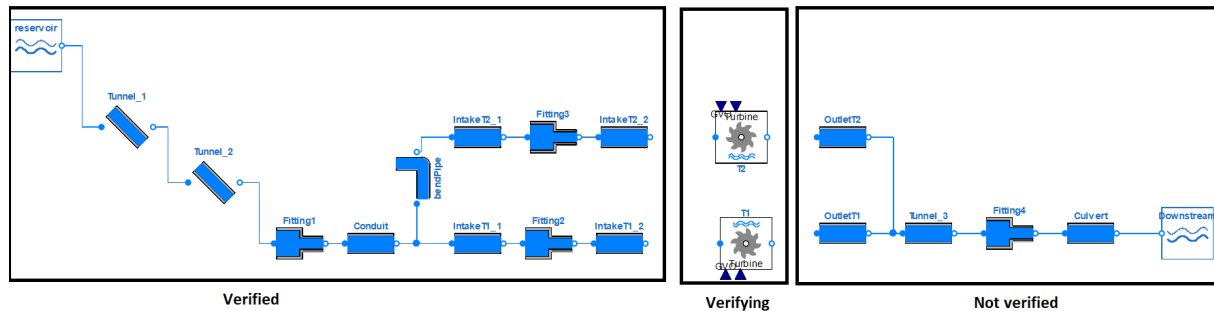


Figure 8.11: Three main parts of hydraulic system model

8.2.1 Experiment 5 - Influence of hydraulic efficiency curves

Objectives recognition The objective of experiment is to consider the influence of hydraulic efficiency curves on generated power of turbine.

Description According to Equation (3.5) and Equation (3.6), generated power of turbine is proportional to hydraulic efficiency and in previous work, original turbine block in OpenHPL only uses with one efficiency curve as input setting. However, as provided by the manufacturer in Appendix D, T1 has five efficiency curves corresponding to flowrate into turbine. This experiment examines how the hydraulic efficiency value from these efficiency curves affect T1 generated power from start-up to steady-state period.

Selection of response The response of interest for the experiment is the generated power of T1.

Selection of process variables There are two variables in this experiment:

- Hydraulic efficiency from five curves of T1
- T1 average of measured opening value of five nozzles in percentage

Evaluation criteria recognition The evaluation criteria of this experiment can be done by the comparison of experimental results and measurement data. Two results are plotted and MAPE is calculated. Similar graphics visualization of two results and $MAPE < 5\%$ are accepted. In addition, the previous experimental results (see Chapter 6) will be included to examine the influence of hydraulic efficiency curves.

Performing the experiment The experiment is implemented as Figure 8.12. The turbine block, flowrate sensor block and hydraulic efficiency block (see Section 7.4.5, 7.4.1 and 7.4.2) are used in this experiment. T2 is forced not to run in this experiment since the objective is to focus only T1.

However, to let the simulation run, it requires an outlet system connected with turbine system. Since the outlet system is not verified, therefore, the simple outlet system is used in this experiment. The simple outlet system consists of OutletT1, OutletT2 same as actual outlet system and new component named "Tailrace" that has the diameter same as Tunnel_3 and the length is the total length of Tunnel_3 and Culvert. The roughness parameter of this "Tailrace" component is set as 0.3. In addition, "bendPipe" component with the loss coefficient as 10 which is the optimal component for branching part shown in experiment 4, will be used in this simple outlet system.

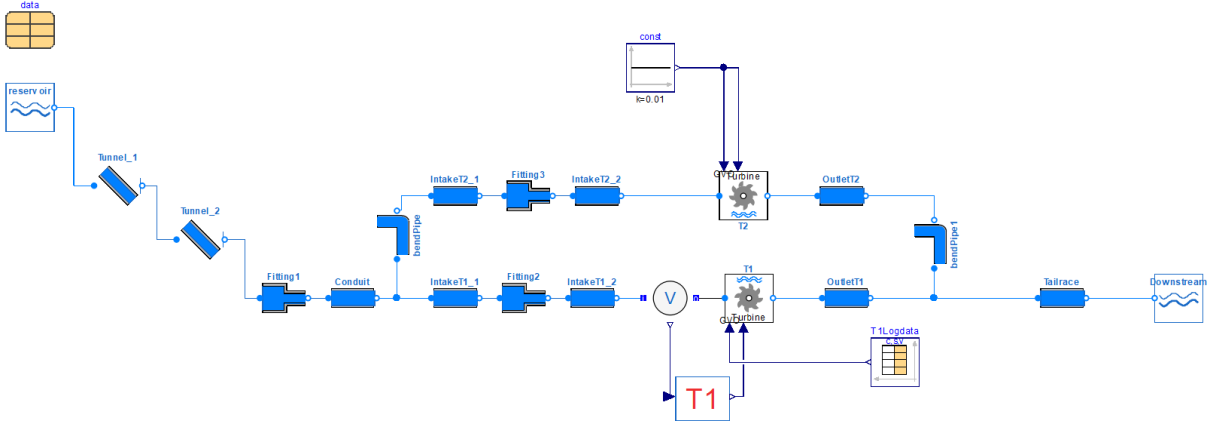


Figure 8.12: Simulation model of experiment 5

Interpreting experimental results The experimental results are collected and plotted in Figure 8.13.

MAPE of this experiment can be resulted in Table 8.9.

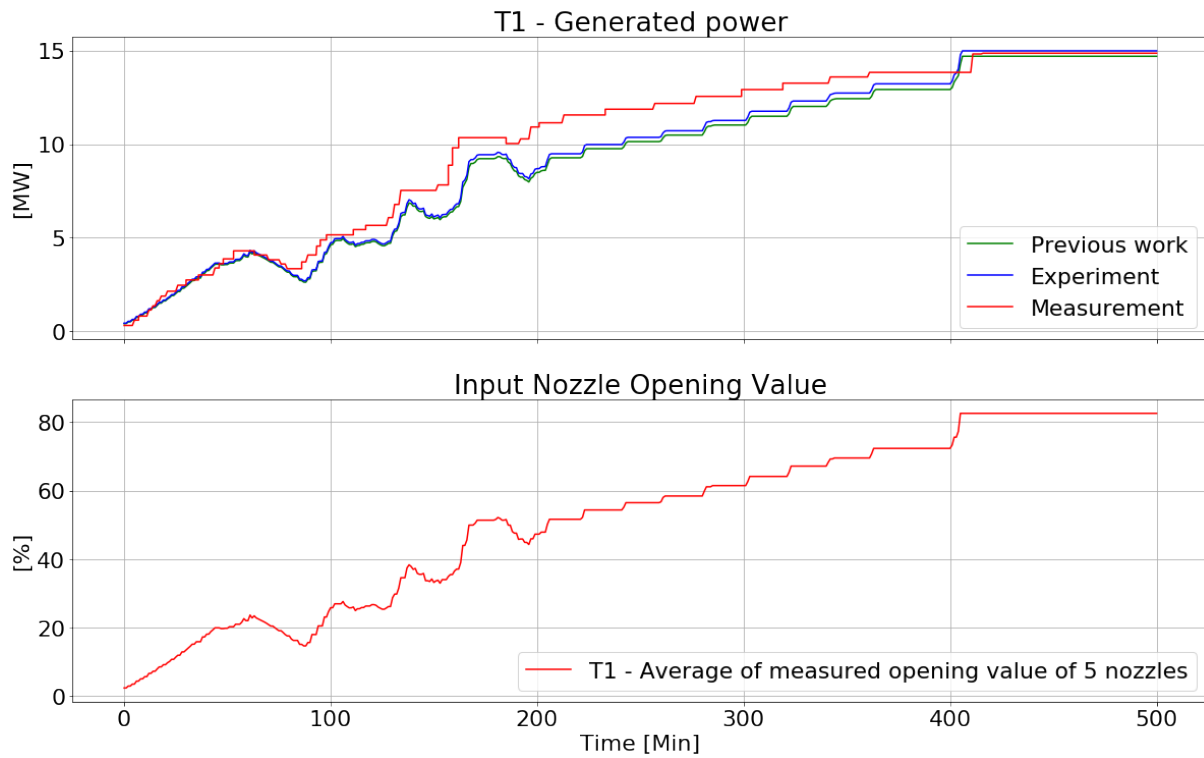


Figure 8.13: Experiment 5 - Comparison of experiment and measurement values

Previous work	Experiment 5
11.38%	10.50%

Conclusions and recommendations According to Figure 8.13, there is large difference between experimental results and measurement values. Comparing experimental results with measurement data, the experiment 5 results show more improvement of T1 generated power than previous work results as illustrated by Table 8.9. However, MAPE of this experiment is large ($>5\%$) that means the large difference between experiment and measured values. Therefore, these difference cannot be accepted.

Through this experiment, it illustrates that the hydraulic efficiency curves do not have large influence to generated power of turbine. However, the hydraulic efficiency curves in experiment 5 shows the improvement of experimental results comparing with previous work results. Hence, these efficiency curves will be applied in later experiments.

8.2.2 Experiment 6 - Mathematical model

Objectives recognition The objective of experiment is to determine the mathematical model showing the relationship between generated power of turbine and nozzle opening value.

Description Experiment 5 showed that there is no large influence from the hydraulic efficiency curves to generated power of turbine. The previous work and experiment 5 used the average of measured opening value of 5 nozzles for the turbine system model to satisfy the turbine block in OpenHPL with one input nozzle opening value signal. However, through two experiments, the difference between experimental results and measurement values is still large. That illustrates the way of applying average of measured opening of 5 nozzles not accurate. The measurement data of opening values of 5 nozzles are only available in dataset used in previous work and experiment 5 and are not available in another dataset. Therefore, this experiment is necessary to determine the relationship of generated power of turbine and nozzle opening value via the mathematical equation.

Selection of response The response of this experiment is the nozzle opening value of turbine blocks, T1 and T2. .

Selection of process variables The variables of interest for the experiment is the generated power of T1 and T2.

Evaluation criteria recognition The evaluation criteria recognition is the accuracy of equation representing the relationship between the response and variable. The accuracy of the mathematical model can be expressed through MAPE with MAPE <5% accepted.

Performing the experiment The experiment is implemented as Figure 8.14

The hydraulic efficiency curve blocks and flowrate sensor block are used in this experiment. Block named “Logdata” contains the nozzle opening values that change from 0% to 100%. The simulation model is performed and the simulation results are collected. The simulation results can be plotted in Figure 8.15.

The next step is to build the mathematical model with the response as nozzle opening values and variable as generated power of turbine.

The collected simulation results are imported into Python using Pandas library. In Python environment, these data is splitted into random train and test subset with ratio 70:30. In this case, train and test subset include both response and variable values of simulation

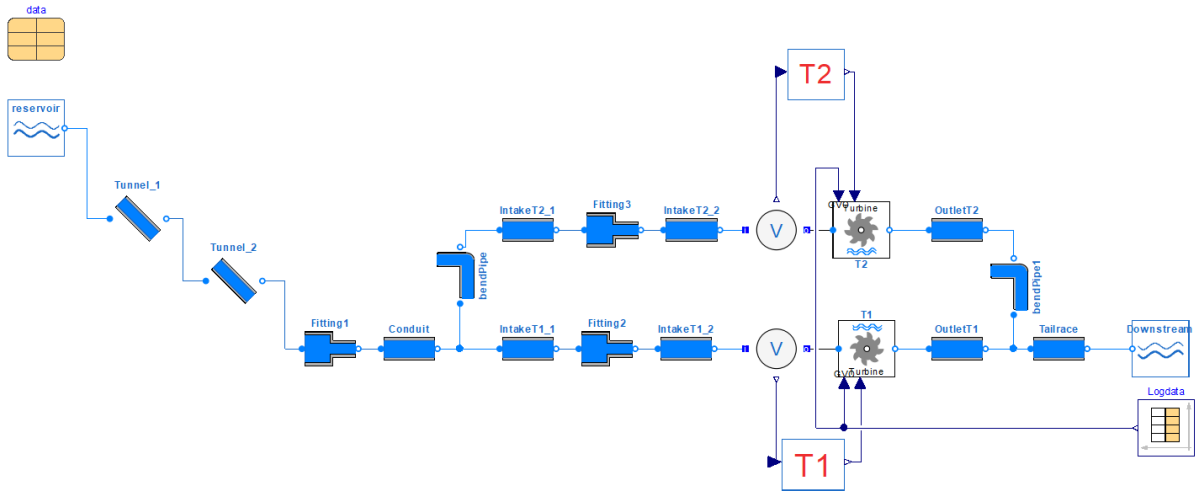


Figure 8.14: Simulation model for experiment 6

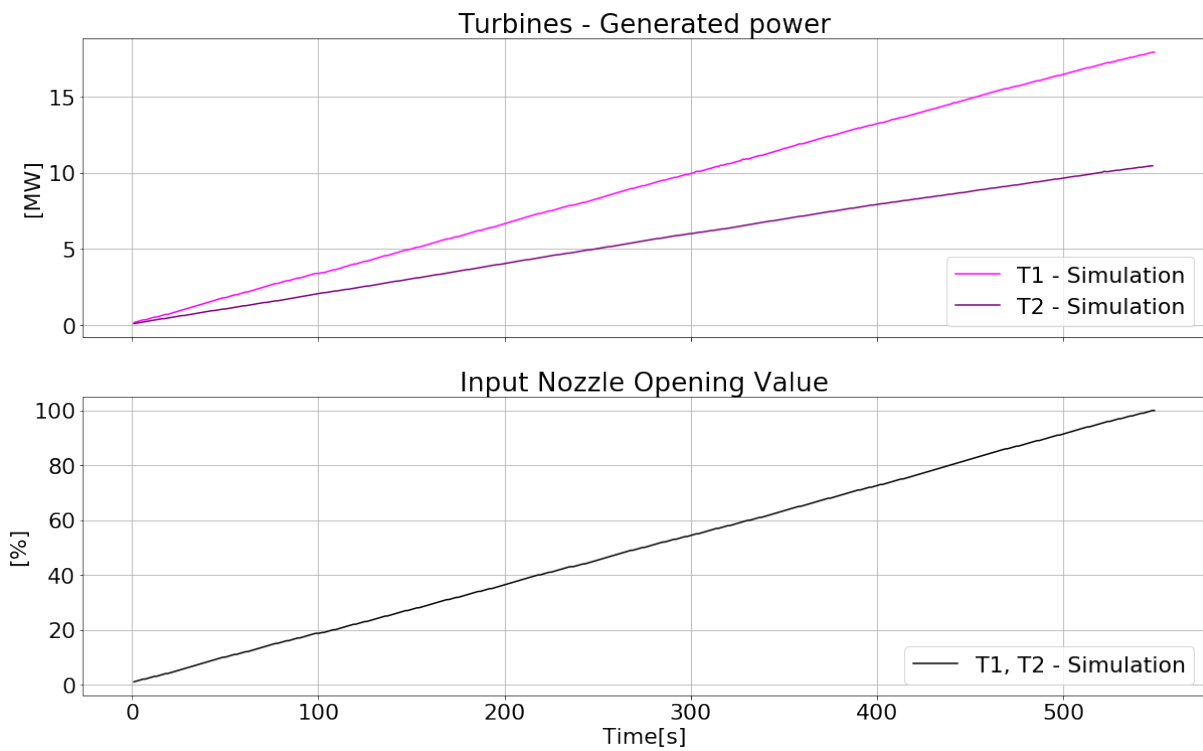


Figure 8.15: Experiment 6 - Collected results from simulation model

results. However, train subset only consist of 70% and test subset contains 30% amount of collected simulation results.

The train subset is used to build mathematical model between its response and variable

by using linear regression command of scikit-learn package (see Section 7.5). Test subset is used to examine the accuracy of the built mathematical model. The variable of test subset are used in mathematical model to calculate the response. This response from mathematical model is called calculated response. And these values are compared with the response in test subset as known as actual response.

Interpreting experimental results The mathematical model represents the relationship between generated power and nozzle opening value depending on Equation (2.3), that can be illustrated after performing the experiment as following:

T1 mathematical model:

$$y = -0.0036 + 5.54 \times 10^{-8}x \tag{8.1}$$

T2 mathematical model:

$$y = -0.0049 + 9.48 \times 10^{-8}x \tag{8.2}$$

Where:

x - Generated power of turbine [W]

y - Nozzle opening value [%]

By splitting into two subsets, the actual response is the nozzle opening values in test subset and calculated response is the nozzle opening values gained from mathematical models based on generated power of turbines from test subset.

The actual response and calculated response from T1 and T2 mathematical model can be illustrated in Figure 8.16.

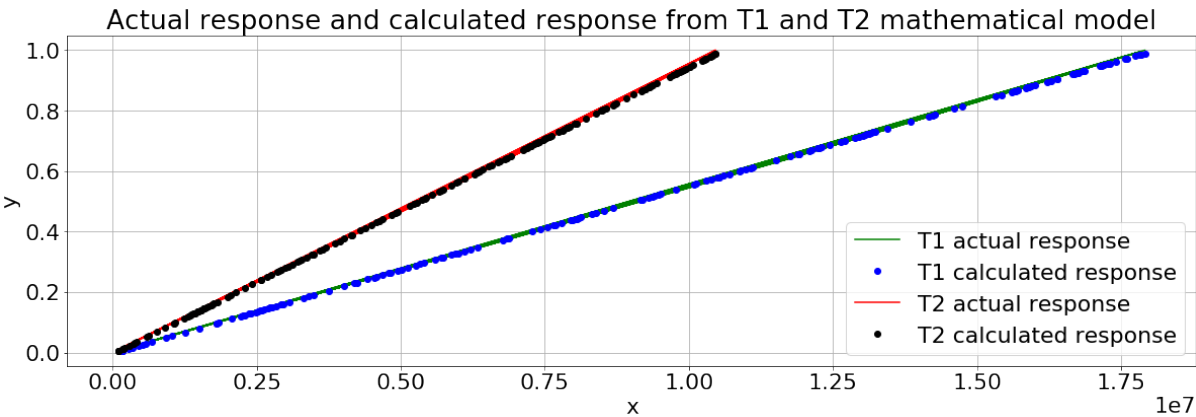


Figure 8.16: Experiment 6 - Actual response and calculated response from T1 and T2 mathematical model

MAPE of this experiment is depended on calculated response and actual response that can be resulted in Table 8.10.

Table 8.10: MAPE of experiment 6

T1 mathematical model	T2 mathematical model
2.84%	3.76%

Conclusions and recommendations Figure 8.16 shows the nearly similar characteristic between calculated and actual values. In addition, MAPE of T1 and T2 mathematical model are resulted as Table 8.10, 2.84% and 3.76%, respectively that are both lower than 5%. Therefore, the mathematical model, Equation (8.1) and Equation (8.2) are acceptable to represent the relationship between generated power and nozzle opening value. These parameters of the equation will be used to build the nozzle opening block (see Section 7.4.3) and will be used in next experiments.

8.2.3 Experiment 7 - Verify mathematical models

Objectives recognition The objective of experiment is to verify the calculated nozzle opening value from mathematical models in experiment 6.

Selection of response The response of interest for the experiment is the generated power of T1.

Selection of process variables The calculated opening value of nozzle from T1 mathematical model.

Evaluation criteria recognition The evaluation criteria of this experiment can be done by the comparison of experimental results and measurement data. Two results are plotted and MAPE is calculated. Similar graphics visualization of two results and MAPE < 5% are accepted.

Performing the experiment The experiment will be performed as Figure 8.17. The hydraulic efficiency curve block, turbine block and nozzle opening block are used. The T1 nozzle opening block includes the parameters of Equation (8.1). In this experiment, T2 is forced to be stop since the objective of this experiment is to focus only T1.

Interpreting experimental results Experimental results are collected and can be plotted in Figure 8.18.

MAPE of this experiment can be resulted in Table 8.11.

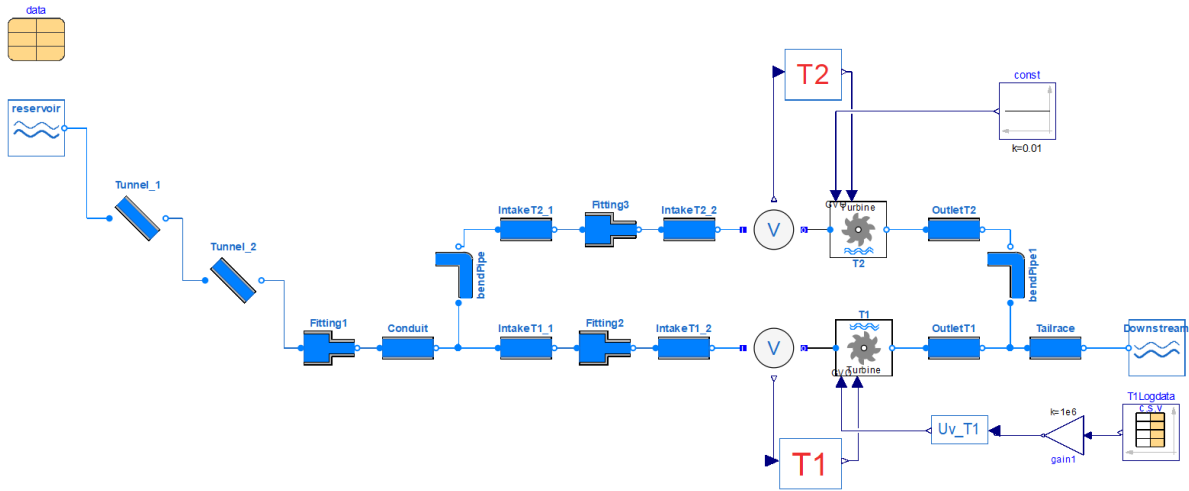


Figure 8.17: Simulation model for experiment 7

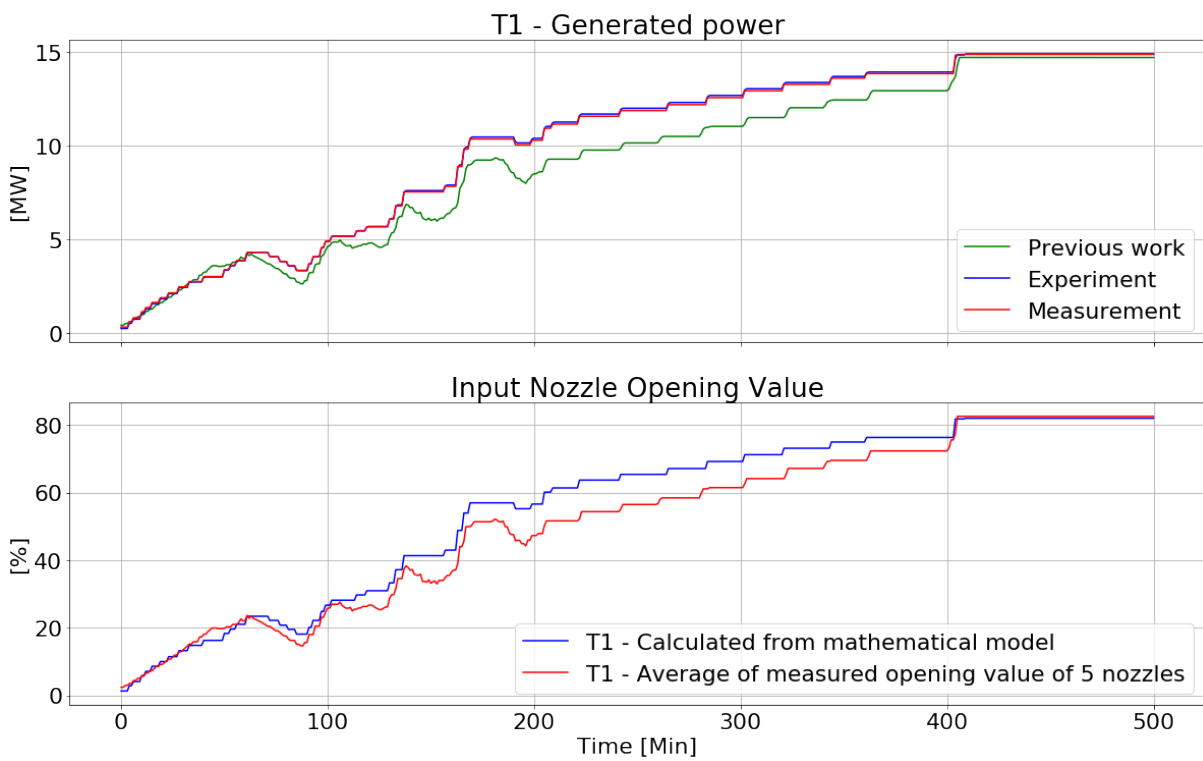


Figure 8.18: Experiment 7 - Comparison of experiment and measurement values

Conclusions and recommendations According to Figure 8.18, the experiment 7 results illustrate the similar trend and no large difference comparing with generated power of turbine from measurement due to MAPE as 0.77%. Therefore, the calculated opening

Experiment 7	Previous work
0.77%	11.38%

value of nozzle from mathematical model in experiment 6 is acceptable and can be used to calculate nozzle opening value for turbine block in simulation model corresponding to the measured generated power of turbine.

Confirmation run Another dataset is used for confirmation run of this experiment. The challenge is that these dataset do not have the information about the measured nozzle opening values of turbine, only have the values of generated power of turbines. These values are used to calculate the nozzle opening values by Equation (8.1) and Equation (8.2). The calculated nozzle opening values are applied for simulation model. To perform confirmation run, the experiment is set as Figure 8.19 and hydraulic efficiency block, nozzle opening block of two turbines are used in this confirmation run. The nozzle opening block includes the parameters of Equation (8.1) and Equation (8.2).

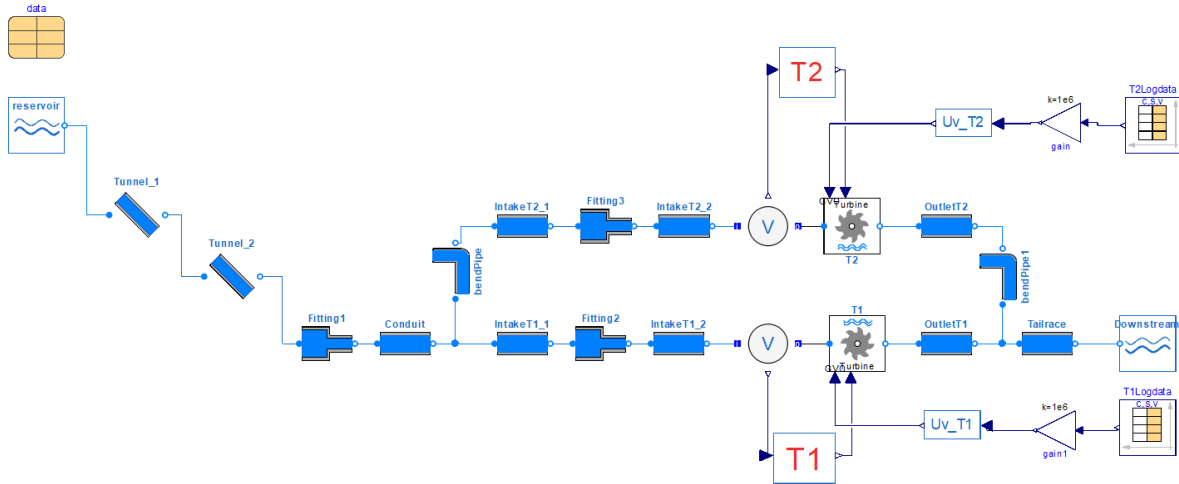


Figure 8.19: Simulation model for confirmation run in experiment 7

The confirmation run results are collected and plotted in Figure 8.20 and Figure 8.21. MAPE of confirmation run can be resulted in Table 8.12.

T1 confirmation run	T2 confirmation run
1.11%	1.17%

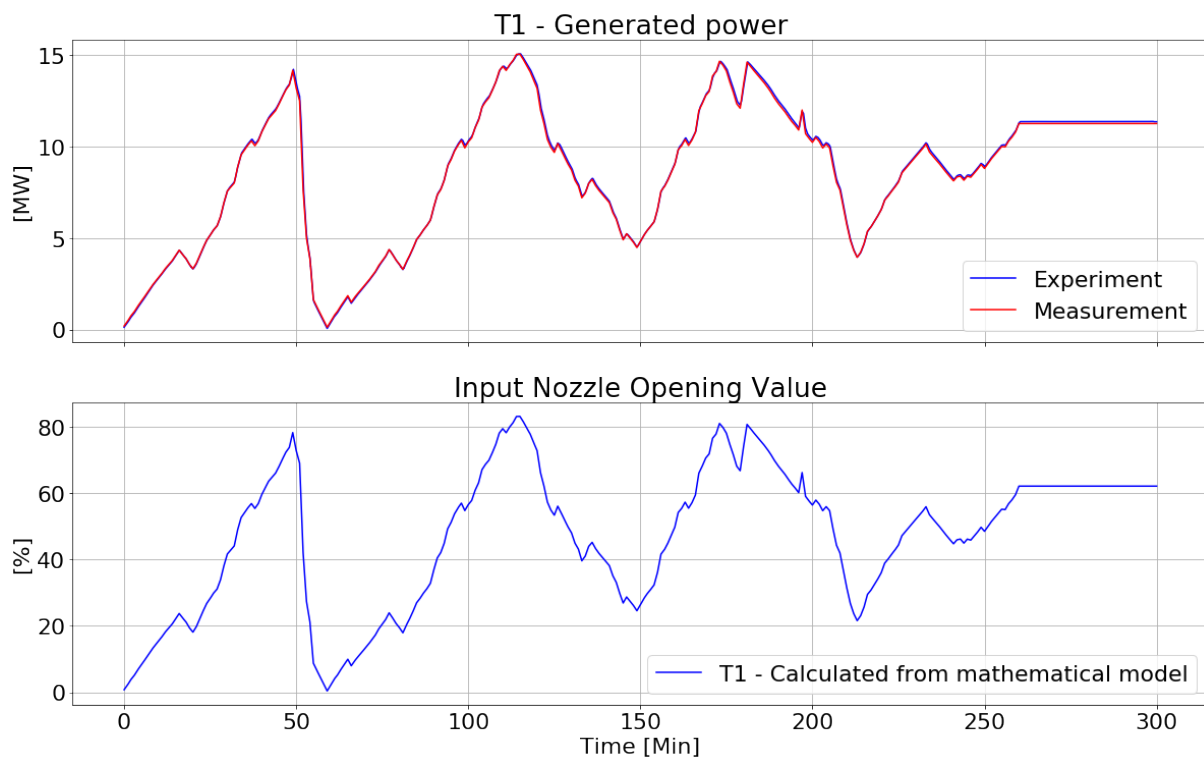


Figure 8.20: Experiment 7 - Confirmation run using mathematical model of T1

With same evaluation criteria in experiment 7, through confirmation run of this experiment, the mathematical models of T1 and T2 in experiment 6 are acceptable to be accurate.

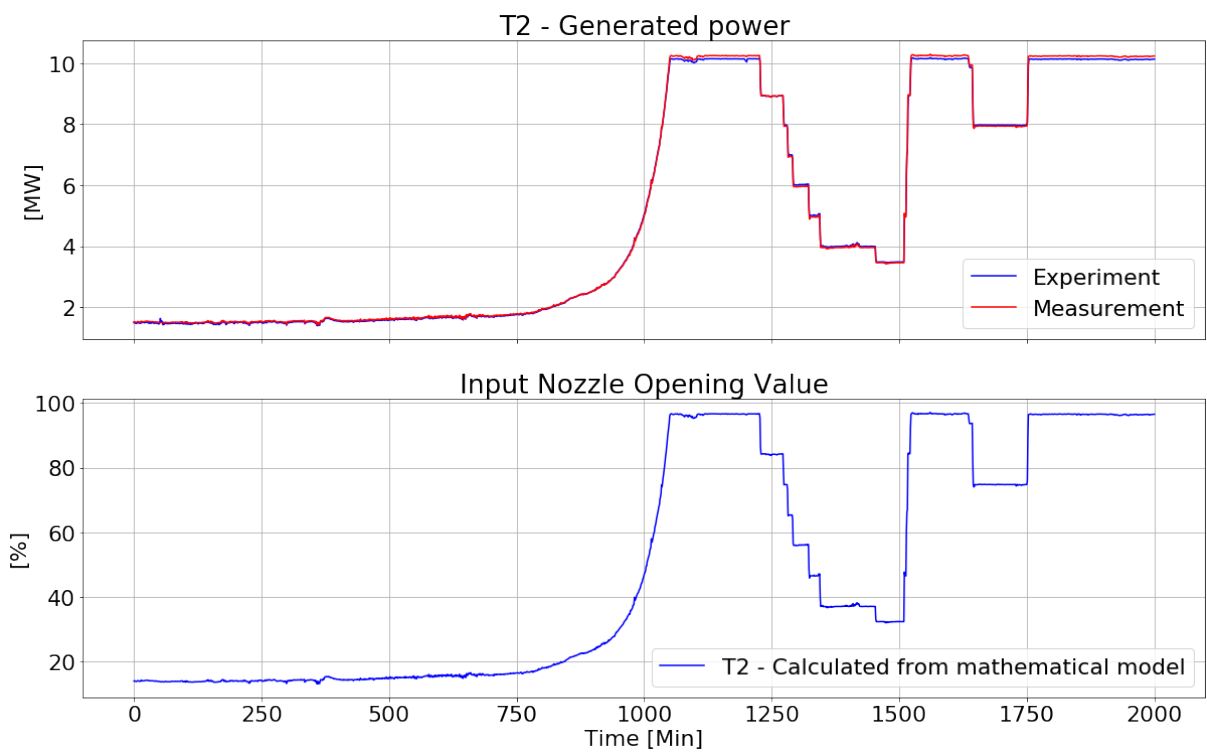


Figure 8.21: Experiment 7 - Confirmation run using mathematical model of T2

8.3 Outlet System Experiment

The experiment on outlet system of hydraulic system in hydropower plant model is to complete the simulation model. Because of the lack of component in OpenHPL, "Open-Channel" block that can be shown in [62], the experiment on this system is mainly to verify and confirm the design of outlet system in reality. The elements in this system are OutletT1, OutletT2, Tunnel_3 and Culvert due to Table 4.1.

8.3.1 Experiment 8 - Culvert diameter

Objectives recognition The objective of experiment is to verify and confirm the design of the actual outlet system.

Selection of response The response of interest for the experiment is height of water level in the culvert.

Selection of process variables The variable in this experiment is the diameter of culvert.

Evaluation criteria recognition According to the objective of this experiment, the height of water level in the culvert is examined with the diameter of culvert in the real-world power plant. Water level in the culvert at zero means good drainage and demonstrates the right design of diameter of culvert.

Performing the experiment The experiment is implemented as Figure 8.22. The parameters of elements in this experiment are set according to the geographical data from Table 4.1.

The blocks named "T1" and T2 are "Volume flow source" block with having setting of nominal flowrate of two turbines. Furthermore, from experiment 3 and experiment 4, the block "bendPipe" as loss coefficient parameter, 10, showed that it is a good component illustrating the branching part, therefore this component are used in this experiment.

Using sweep parameters in Dymola/Modelica with the change in diameter in component "Culvert" from 0.5m to 3m and get the corresponding values of water pressure in "Culvert" component. These pressure values are used to calculate the height of water level in Culvert by Equation (3.2).

Interpreting experimental results The experimental results are collected and plotted in Figure 8.23.

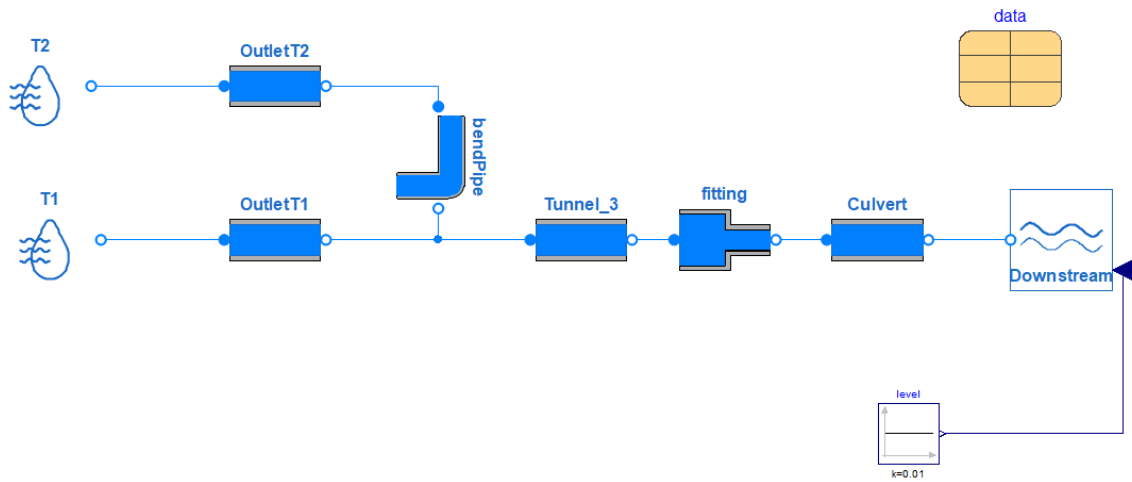


Figure 8.22: Simulation model of experiment 8

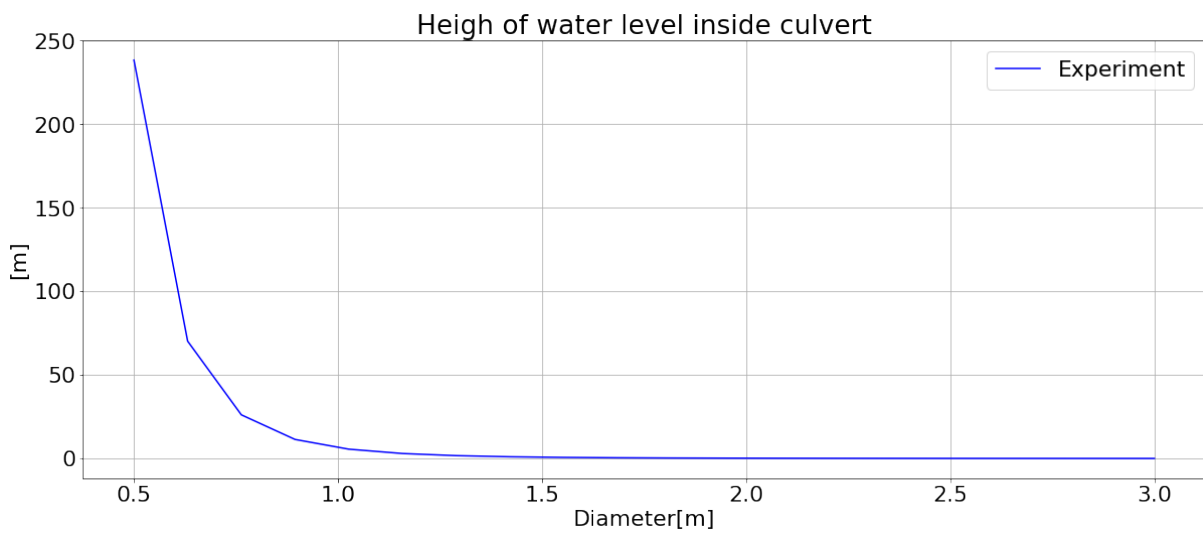


Figure 8.23: Change the water level in the culvert according to its diameter

Conclusions and recommendations According to Figure 8.23, with the setting of nominal flowrate of two turbines, the height of water level inside culvert is zero. It illustrates that the diameter of culvert in actual power plant as 2m, satisfied the amount of water discharged and ensured the nominal operation of two turbines.

Furthermore, if the diameter of culvert is small, the capability of discharging outlet water from two turbines is low leading to the full of water inside the tunnel and flowing to two turbines causing the damage to turbines and the power plant that can be seen from

Figure 8.23 with 0.5m diameter of culvert leading to 250m water level. In this case, the diameter of culvert is above 1m to satisfy the capability of discharging outlet water.

Hence, with this experiment, the design of diameter of culvert in the actual power plant is accurate and shows full capability of discharging the outlet water in nominal operation condition of the power station.

Through set of experiments on hydraulic system model, the complete model of this system can be shown in Figure 8.24.

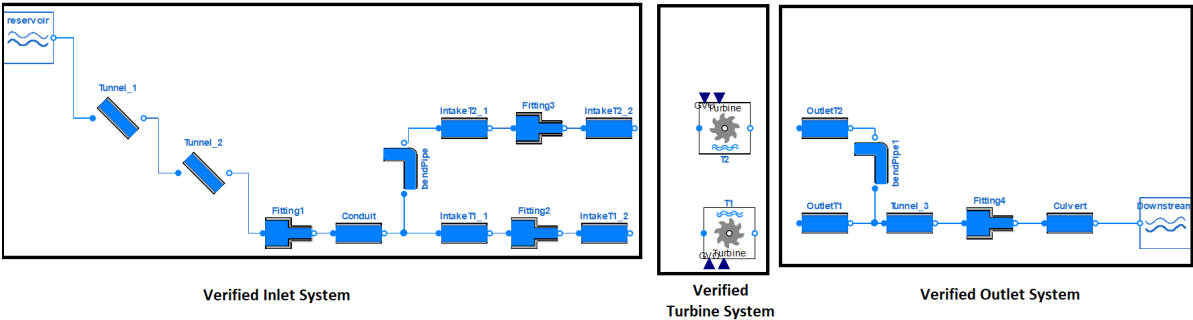


Figure 8.24: Complete model of hydraulic system with three verified and optimized parts

8.4 Electrical System Experiment

8.4.1 Experiment 9 - Voltage drop

Objectives recognition The objective of experiment is to verify the voltage drop across transmission system of G1 branch under the change of load.

Selection of response The response in this experiment is the voltage drop magnitude.

Selection of process variables The variable in this experiment is the value of the load.

Evaluation criteria recognition The similar values of voltage drop magnitude from calculation and simulation can be accepted.

Performing the experiment The information of elements in electrical system model is in [4].

The experiment of simulation model is implemented as Figure 8.25 with the load change from 1 MW to 15 MW. In this experiment, input mechanical power of generator block is set at constant.

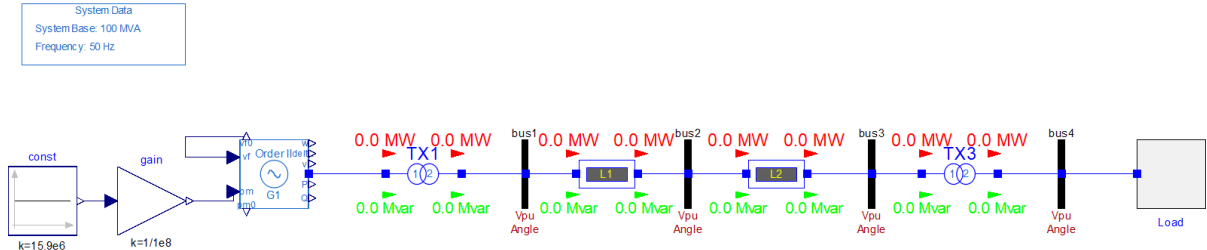


Figure 8.25: Simulation model of experiment 9

The calculation of this experiment can be shown in Appendix C.

Interpreting experimental results The experimental results are collected and plotted in Figure 8.26.

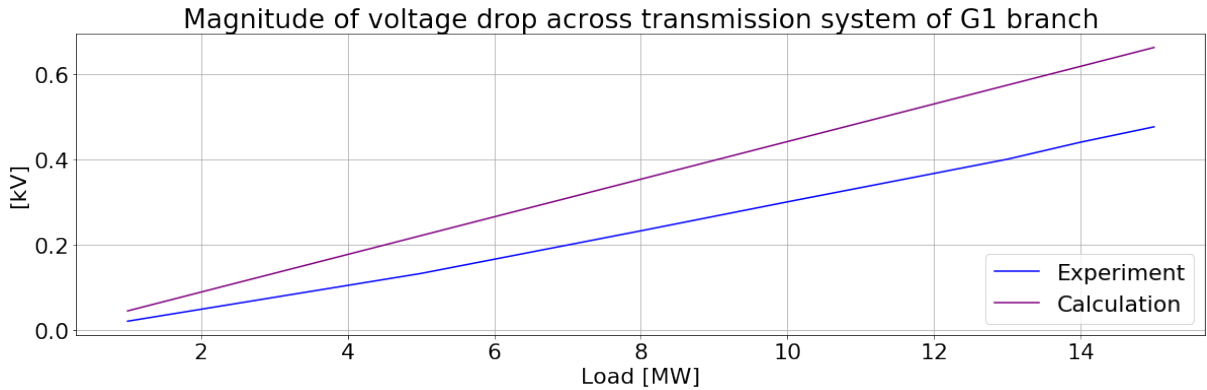


Figure 8.26: Experiment 9 - Comparison between experiment and calculation values

Conclusions and recommendations According to Figure 8.26, with the increase of load values, the voltage drop across transmission system from calculation and experiment also increases. However, these results are different that requires measurement data in electrical system to verify calculation and experiment results from electrical system model.

9 Discussion

The main purpose of this thesis was to apply "Design of Experiments" methods to verified hydropower plant simulation model created by OpenHPL in Dymola/Modelica regarding to available data from measurement system of the power plant.

This chapter consists of three parts: Measurement data, DoE method which aimed to detail and evaluate the DoE applications to experiments of verification; and Experiments.

9.1 Measurement Data

There are several sensors located in hydropower plant with different labels. In progress of preparing data for experiments, it is difficult to recognize the sensors measuring in which components in the power plant. The names of measurement data from Table 4.4 based on the labels of sensors, therefore, are modified to get easier understanding about the measurement data in this report.

The provided data from sensors which was used in this report, are combination data at different point of time at previous work and this semester. Since the different operating conditions of hydropower plant depended on the change of seasons, some of measurement data at component units in the power plant is not available, therefore, measured values in experiments can be retrieved from different times and data sources.

The tolerances of typical sensors from Table 4.5 show the low value illustrating the reliability of sensors from the manufacture, however, in the realistic power plant, the measurement system is influenced different bias from environment, operating conditions, etc. The provided data from some sensors showed the inaccurate values and filtered out of used measurement data. Measurement names in Table 4.4 are considered as reliable, accurate data source.

The lack of measurement data in electrical system leads to situation where experiment of electrical system model did not have reference values and is replaced by calculated values. To verify the electrical system model, it requires measurement data in this system to examine the accuracy of simulation and calculated results.

9.2 DoE Method

9.2.1 DoE Principles

DoE has blocking, repetition and randomization that are fundamental principles for setting experiment configurations. These rules are useful in real-world experiments since there are appearance of environment bias or uncontrollable factors. For simulation model, that is created by combination of massive mathematical equations along with logical principles, therefore, there is almost no influences from environment or operation procedures in real-world. Components of model are built by input parameters from realistic system and it is easy to recognize with missing information of component's input parameter and they are taken into consideration.

The blocking principle is extremely helpful in the experiments that divides the model into several portions and conducts to verify each portions to gain the completed and reliable final model.

Replication shows a helpful support for blocking which replicates each portions under various conditions to ensure the reliability of final given conclusion of experiment before moving to next experiment and this is important, especially experiments having sequence.

The principle, randomization, is useful for simulation model in a situation where it is difficult to select suitable design elements or suitable parameters for components in simulation model. In hydraulic system model, this principle is applied to select randomly the parameter of roughness factor of tunnel units in experiment 2 and loss coefficient of "bendPipe" component in experiment 4. In experiment 3, there are only three designs for branching part in experiment 3 and in case of many elements in library, this principle can be applied to select randomly elements and perform experiments on these elements to get suitable option.

9.2.2 DoE Steps

DoE procedures from first step, object recognition, to last step, conclusions and recommendation, (see Section 2.4) have a sequence and close relationship with each other. These contribute to a systematic and organised experimental performance that helps to make specific experiment plan as well as implementation steps under vast amount of data.

In progress of performing experiments, the step of evaluation criteria recognition is added in the set of DoE procedures that is different than cited documents such as [5] or [7]. In simulation model required high accurate results, it is necessary to figure out criteria to

compare the simulation results with reference values, not only the results shown in plot, therefore, MAPE is also included.

This step is added in this report as standard helping recognize the success or failure of experiment. In addition, the criteria of MAPE in experiments is usually set at lower than 5% from [61] which is considered as reference criteria under comparing with measurement data. In other experiments of simulation model, MAPE can be set at lower depended on the objective of simulation model and the reliability of reference values.

Step 4, selection of experimental design, is obtained to figure out the type of experiment design for the experiment as well as calculating the number of experiment runs. This step is extremely effective for planning real-life experiments to avoid resources and time consuming by including main impact variables, their interaction and their levels. However, the simulation model with time-varying variables was performed on the software including a series of levels in time series, so the experiments on the simulation model are totally done by OFAT method.

9.3 Experiments

Experiments on inlet system model were mainly used measured flowrate and pressure data. Through experimental results in experiment 1 to 4, it can be seen that when the water flowrate increases, the water pressure decreases. This can be explained by Bernoulli principle that is “In water or air currents, if the velocity is low, the pressure is high. If the velocity is high, the pressure is small” [63].

The inlet system model of hydropower plant is created based on OpenHPL in Dymola. Through experimental results, specifically, experiment 1 showed the similar results between simulation and measurement, however, the simulation illustrated the lower response than the measurement data as well as peak-peak values are higher than measurement data. This comes from the components built in OpenHPL. The model used mainly “Conduit” block in OpenHPL that is elastic conduit and is the main reason for the difference between simulation and measurement results. The influences and comparison between elastic and inelastic components can be illustrated in [64].

Through experiment 1 and experiment 2, the difference of results from experiment and previous work is considered. The inaccurate setting of block “fitting” in the simulation model of previous work is the culprit of this discrepancy. Therefore, through experiments of verification, the error of previous work model can be figured out.

In turbine system experiment, original turbine block in OpenHPL used in previous work only contains one input nozzle opening value. This block can be used in case of turbine having one nozzle. However, in case of more than one nozzle same as T1, the average of opening value of nozzles is used for this input and this way showed the inaccuracy

through previous work and experiment 5. Therefore, the mathematical model between nozzle opening value and generated power of turbine was created through experiment 6. This model is useful in case of no information of measured opening values. In reality, based on this mathematical model, the necessary opening value of nozzle can be calculated according to desired power.

It is noted that the generated power of turbines illustrated in previous work and set of experiments on turbine system is power at the shaft of turbine that matches with provided measurement data in Table 4.4. According to Equation (3.6) and Equation (3.7), the power at the shaft of turbine is influenced by hydraulic and mechanical efficiency. Hydraulic efficiency can be shown in Appendix D while the mechanical efficiency is not available in this thesis. However, the mechanical losses were provided by Skagerak Kraft AS company and were considered as constant in this thesis during the different operating periods of turbines and were applied in turbine block illustrating in [4].

10 Conclusion and Further Work

10.1 Conclusions

The experiments of verification of simulation model of Grunnåi hydropower plant as a typical hydropower plant, was executed in this Master's Thesis where "Design of Experiments" method was applied. This study was mainly focused on application of DoE method on planning, performing experiments on simulation model with the purpose of verifying and optimizing the model under vast amount of measurement data.

DoE method including fundamental principles, experimental procedures and statistical background shown in this report was used as a foundation of experiments on simulation model, which aimed to verify and optimize the model. These set of experiments figured out the variables having strong influences to the model and examined the uncontrollable factor impacts. In addition, the relationship between variables and response have been given by mathematical model depended on statistical background of DoE. Overall, through experiments of verification, the complete and optimized simulation model was established that produces high reliable and accurate results.

In progress of executing experiments, the vast amount of measurement data provided by Skagerak Kraft AS must be analyzed and cleaned according to necessary quantities in different dataset. This thesis also contributed effective and efficiency data analyzing method that will be used in experiments. In addition, not all the provided measurement data is totally accurate, the complete simulation model have capability of examining the data from measurement system of hydropower plant and proposing measurement locations to gain the two-way system monitoring. Through existing work in this project, the factors affecting realistic hydropower plant such as roughness factor of waterway, hydraulic efficiency or nozzle opening value were taken into account and given in this report that lays a groundwork for future research in hydropower plant.

In the significant increase of simulation tools and software, this thesis basically contribute the simple and effective method to verify and optimize the simulation model in different engineering field that helps satisfying further study and research in the future.

10.2 Further work

The simulation model of Grunnåi hydropower plant was not totally verified such as electrical system because of the lack of measurement data. The model of this system will be verified in the future after having available data in this system.

This simulation model are helpful tools to verify the data from measurement system.

The block named "OpenChannel" in the OpenHPL should be examined and developed to satisfy the simulation model demands.

The turbine block in the OpenHPL should be developed to take as input the number of nozzles helping examining the nozzle opening values.

Machine learning can be applied in the future to predict operating condition and detect error of hydropower plant. The data retrieved from machine learning can be examined in the simulation model to give reliable prediction of the power plant operation.

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Appendix A

Task Description

FMH606 Master's Thesis

Title: Application of Design of Experiments for the Verification of a Hydro Power Plant

USN supervisor: Dietmar Winkler

External partner: Skagerak Kraft AS (Ingunn Granstrøm)

Task background:

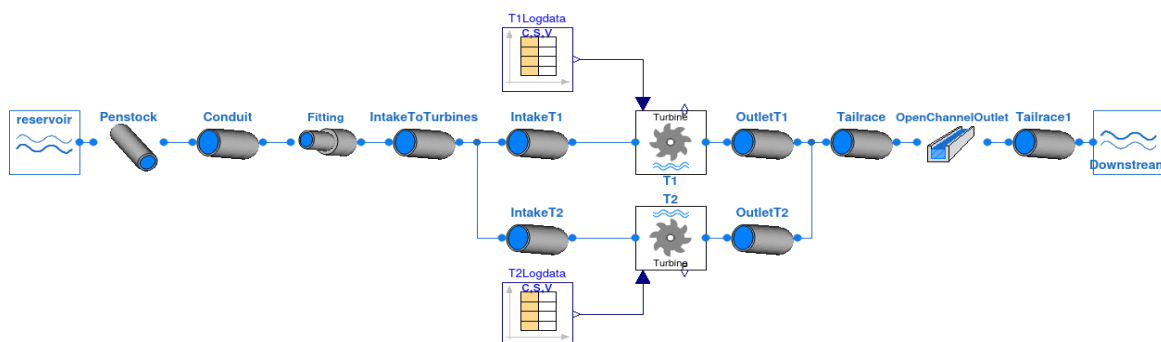
Skagerak Kraft is among the largest power producers in Norway. Each year, the company delivers about 5700 GWh of clean, renewable energy from 48 wholly or partially owned power plants. This is equivalent to the consumption of 285,000 homes, and nearly 4.5 % of the total power production in the country.

The Grunnåi watercourse primarily runs through Seljord municipality in Telemark county. Its outlet is from the east side of the valley at Vallaråi river in Flatdal. The source of the watercourse is Slåkåvatn lake on Lifjell mountain. It is dammed up at the top of Grisejuvet where the intake is also located.

The power plant was commissioned in 2006 and utilises a waterfall height of 387 metres.

In 2019, an extra generator was installed and increased the annual production to 66 GWh. The original generator has an installed capacity of 15.1 MW and an annual output of 55 GWh, while generator 2 has an installed capacity of 10.2 MW and an annual output of 11 GWh.

The new machine can facilitate a research project. It is possible to mount sensors on the impeller, and windows are fitted to the machine making it possible to look into the turbine during production. This allows for logging of high resolution data streams of multiple measurements.



Task description:

In autumn 2021 a model of the water way and electrical connection was modelled as part of a master project. As a continuation of that project now the different parts of the models need to be verified using measurement data from the plant. Because of the vast amount of data available it is crucial to do the verification in an organised and systematic way. This is where the "[Design of Experiments](#)" principle should be applied.

Tasks:

1. Make yourself familiar with the existing Modelica model of the Grunnåi waterway and electrical installation including the [OpenHPL](#) and [OpenIPSL](#) which the model is based on.
2. Familiarise yourself with the "[Design of Experiments](#)" principle with the goal of verification of as many parts of the model as possible.
3. Investigate the available data and the resolution they can be accessed in.
4. Investigate the parameters that can potentially be tuned given the available measurement data.
5. Define dedicated simulation cases in order to obtain data to verify and adjust certain parameters of the models or models themselves.
6. Plan a suitable sequence of simulation cases and which also defines successive simulation cases.
7. Execute the planned simulation cases and adapt the models accordingly
8. Document the carefully the achieved verifications and uncertainties, both in the report and in the test models themselves.

Student category: EPE

Is the task suitable for online students (not present at the campus)? n/a

Practical arrangements:

This thesis requires a very structured working attitude. Models and testcases are to be versioned in Git such that they can be recreated easily at a later point in time. The work will can be executed in Dymola or OpenModelica (possibly in combination with Python).

Supervision:

As a general rule, the student is entitled to 15-20 hours of supervision. This includes necessary time for the supervisor to prepare for supervision meetings (reading material to be discussed, etc).

Signatures:

Supervisor (date and signature):

2022-02-01 

Student (write clearly in all capitalized letters):

LE NAM HAI PHAM

Student (date and signature):

2022-02-01 