

Development of a test bench for dynamic hydroelectric plant control

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Abstract

Hydroelectric plants convert the hydraulic power in flowing water to mechanical energy. The basic technology in a plant has not changed much in the past hundred years but powerful computers and software now allow the construction of virtual models and simulations of hydropower systems. This thesis investigates the feasibility of a construction of a test bench for hydroelectric plants. It is carried out as a collaboration between Chalmers University of Technology and ÅF Industry in Gothenburg. To be able to determine usefulness of the test bench it is validated against existing theory, the simulation software Simpow and real operational data from Hojum G15, a plant in Trollhättan operated by Vattenfall AB. The test bench should have certain features found in a real plant such as frequency control, power output control, island network operations, strong grid network operations etc.

By physical modeling of components found in a hydroelectric plant (such as a turbine, generator and penstock) a simulation model is created. This is done in the simulation software Dymola. The implementation was carried out by describing the system and separate components as differential equations that are solved by the solver in Dymola. To be able to control the model it is connected via an OPC server to a LabVIEW interface. The LabVIEW interface contains all the control sequences in the test bench and has a graphical user interface. Due to Dymola using the DDE communication protocol and LabVIEW using OPC the software application TOP Server has to function as a bridge between the two programs.

The result is a fully functional test bench with a graphical user interface. It simulates a hydroelectric plant that shares a basis of design with the Hojum plant in Trollhättan. It can be run in both island grid mode and strong grid mode. Frequency, voltage, power output and water level control operations can be run.

The system validates against theory and models from the commercial simulation software Simpow. Due to complications with data gathering the validation towards the Hojum plant could not be completed to a satisfying result. It is concluded that a test bench of a hydroelectric plant for educational and training purposes is a feasible concept. However, because of the lack of validation against Hojum the feasibility of other usage areas can not be stated but the concept most certainly seems reasonable.

KEYWORDS: Kaplan, Dymola, Hydroelectric Plant, Generator, Modeling, Control, PLC, LabVIEW, OPC.

Sammanfattning

Vattenkraftverk omvandlar den hydrauliska kraften i strömmande vatten till mekanisk energi. Den grundläggande tekniken i ett kraftverk har inte ändrats mycket de senaste hundra åren, men med mer kraftfulla datorer och programvara är det nu möjligt att bygga virtuella modeller och simuleringar av vattenkraftsystem. Detta examensarbete undersöker genomförbarheten av en konstruktion av en testbänk för ett vattenkraftverk. Avhandlingen genomförs som ett samarbete mellan Chalmers Tekniska Högskola och ÅF Industry i Göteborg. För att kunna bedöma nyttan av den slutgiltiga testbänken har den validerats mot befintlig teori, simuleringsprogramvaran Simpow och verkliga operativa data från Hojum G15 som är ett vattenkraftverk i Trollhättan som drivs av Vattenfall AB. Testbänken skall ha vissa funktioner som finns i en riktig anläggning detta så som bl a frekvenskontroll, pådragskontroll, ö-drift, och drift mot starkt nät.

Genom fysikalisk modellering av de komponenter som finns i ett vattenkraftverk (till exempel en turbin, generator och dammluckor) kan en simuleringsmodell skapas. Detta görs i simuleringsprogramvaran Dymola. Implementeringen utförs genom att beskriva systemet och separata komponenter som differentialekvationer vilka löses i Dymola. För att kunna styra modellen är den ansluten via en OPC server till ett LabVIEW gränssnitt. I LabVIEW finns alla regler- och styrsystem samt ett grafiskt användargränssnitt. På grund av att Dymola använder kommunikationsprotokollet DDE och LabVIEW använder sig av OPC har programmet TOP Server installerats som en brygga mellan de två programmen.

Det slutgiltiga resultatet är en fullt fungerande testbänk med ett grafiskt användargränssnitt. Den simulerar ett vattenkraftverk som i stora drag har samma design som kraftverket Hojum, Trollhättan. Testbänken kan köras i ö-drift och mot starkt nät. Styrsystemet i testbänken har bl a frekvensreglering, spänningsreglering, effektreglering och vattennivåreglering.

Systemet överensstämmer bra med teori och modeller från det kommersiella programvaran Simpow. Dock kunde validering mot Hojum-anläggningen inte slutföras med ett tillfredsställande resultat. På grund av att insamlad data var otillräcklig i detaljnivå. Testbänken uppskattas att vara väl duglig i t.ex. utbildningssammanhang. På grund bristande valideringen gentemot Hojum går det inte att med tillräcklig säkerhet fastställa om testbänken kan användas mot ett skarpt system. Dock finns det klara indikationer på att konceptet i sin helhet är väl genomförbart.

NYCKELORD: Kaplan, Dymola, Vattenkraftverk , Generator, fysikalisk modellering, reglerteknik , PLC, LabVIEW, OPC.

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1 INTRODUCTION

This master thesis treats the construction of a simulation test bench for hydroelectric plants. It is carried out as a collaboration between Chalmers University of Technology and ÅF Industry in Gothenburg which is a part of the ÅF Group. ÅF is a technical consulting company, offering services and solutions in various fields such as infrastructure, IT and industrial projects.

1.1 Background and Previous Work

Hydropower is the principle of generating power by converting the hydraulic power in flowing water to mechanical energy. Man has used hydropower for centuries to assist her with tasks like irrigation or operating various machines such as watermills, cranes etc. Since the last century it has been used to generate electricity in hydroelectric power plants.

In Sweden there are about 1800 hydroelectric plants which produces 48.8% of electricity production, thus making it the single largest renewable energy source. Globally hydro electric power is the most important renewable energy source, producing 16.8% of the world's total production [14].

Even if the basic technology of a hydroelectric plant is the same as a hundred years ago, the control and government of a plant has been computerized during the last decades. This in combination with more powerful computers and software allows the construction of virtual models and simulations of hydropower systems. Models and simulation of a plant can be used in various ways such as optimization of various components or sub-systems, off-line programing, test and verification or they may function as a learning platform to increase the knowledge and understanding of how the system works.

Naturally, being a major power source there is a lot of research regarding hydropower and hydroelectric plants including test benches and simulation studies, (Taylor et al 1976). Simulation studies have also been made with the software used in this thesis, Dymola. For example has Modelon AB [12] developed a complete Modelica Library for Simulations of Hydro Power Plants. Another master thesis (see [8]) has investigated the task in constructing a hydropower library modelica library as well.

1.2 Thesis Objectives

The main objective of this work was is to develop a functional test bench of a hydroelectric plant. This can be divided into the following sub-goals:

- To develop a model of a hydroelectric plant and an electrical grid in Dymola using the modeling language Modelica. The model will be developed in a object-oriented sense as much as possible, thus dividing the system into sub-components such as turbine, penstock, reservoir, generator, electrical grid, electrical load etc.
- To design an interface for the system in LabVIEW.
- To develop different types of governing systems for the model. This should at least include frequency control and power control.
- To establish communication between the hydroelectric plant model in Dymola and LabVIEW.
- To validate the model against an existing system to the largest extent possible.

The main difference between the objectives above and the existing work mentioned in 1.1 is the development of the interface and the communication.

The main purpose is to test to what extent it is possible to develop a test bench of a hydroelectric plant and investigate its usefulness. A test bench of a hydroelectric plant may be used for several purposes, for example:

- Work as a teaching platform to train staff and increase knowledge and understanding.
- Test and verify different operating scenarios off-line, thus potentially reducing costs.
- Test and develop existing and new control strategies.

1.3 Method

The development of the test bench was carried out in two phases.

- Modeling - The system is modeled according to theory. As stated above has been done in Dymola. At first the whole hydroelectric plant, including the control system, was tested in Dymola. When functionality is verified the control system was removed from Dymola and moved into LabVIEW together with the interface.
- Interface design, Communication and Validation - An interface was designed using LabVIEW from National Instruments that controls the Dymola model. Finally, the model was verified and validated. This was done in collaboration with Vattenfall and the Hojum Hydroelectric Plant in Trollhättan, Sweden in the form of comparing real data against the model output.

2 MODELING

Below follows the general information about the physical characteristics of hydroelectric plants and how it can be mathematically modeled. The modeling is divided into the following sub-parts:

- *General Description* - A general description over the workings of a hydroelectric plant.
- *Overview of Modeled System* - Presents details of the Hojum plant in Trollhättan and an overview of the modeled parts that has been used in the test bench and how they interact.
- *Process* - Concerns the physical modeling of the mechanical and the fluid parts of a plant.
- *Electrical* - Concerns the physical modeling of generator, load and grid.
- *Control Theory* - Different types of control that was used to control the Hydro power plant.

2.1 General Description of Hydroelectric Plants

As stated in Section 1.1 hydroelectric plants work on the principle of converting the potential energy between two water levels, first into mechanical power and later into electrical power. Below in 2.1.1 the main components of a plant are shown. The basic principle is that water flows from a reservoir or river through a penstock and powers a turbine which creates a mechanical torque and rotational speed which generates electrical power from a generator. Gross power, P_{gross} [W], generated by the plant is dependent on the discharge Q [m³/s] and the gross water head H_{gross} [m] according to [9]

$$P_{gross} = \rho Q g H_{gross} \eta. \quad (2.1.1)$$

In Equation 2.1.1 ρ is the density of water and η is the turbine efficiency. The gross head H_{gross} in a plant is defined as the height between the water level of the reservoir and water level of the outlet destination, in Figure 2.1.1 this would be reservoir level minus the water level of the river. There is also a net head:

$$H_n = H_{gross} - H_L, \quad (2.1.2)$$

where H_L is the sum of all the losses in head throughout the system due to friction, turbulence and so forth. The net power P_n [W] acting on the turbine then becomes

$$P_n = \rho Q g H_n \eta, \quad (2.1.3)$$

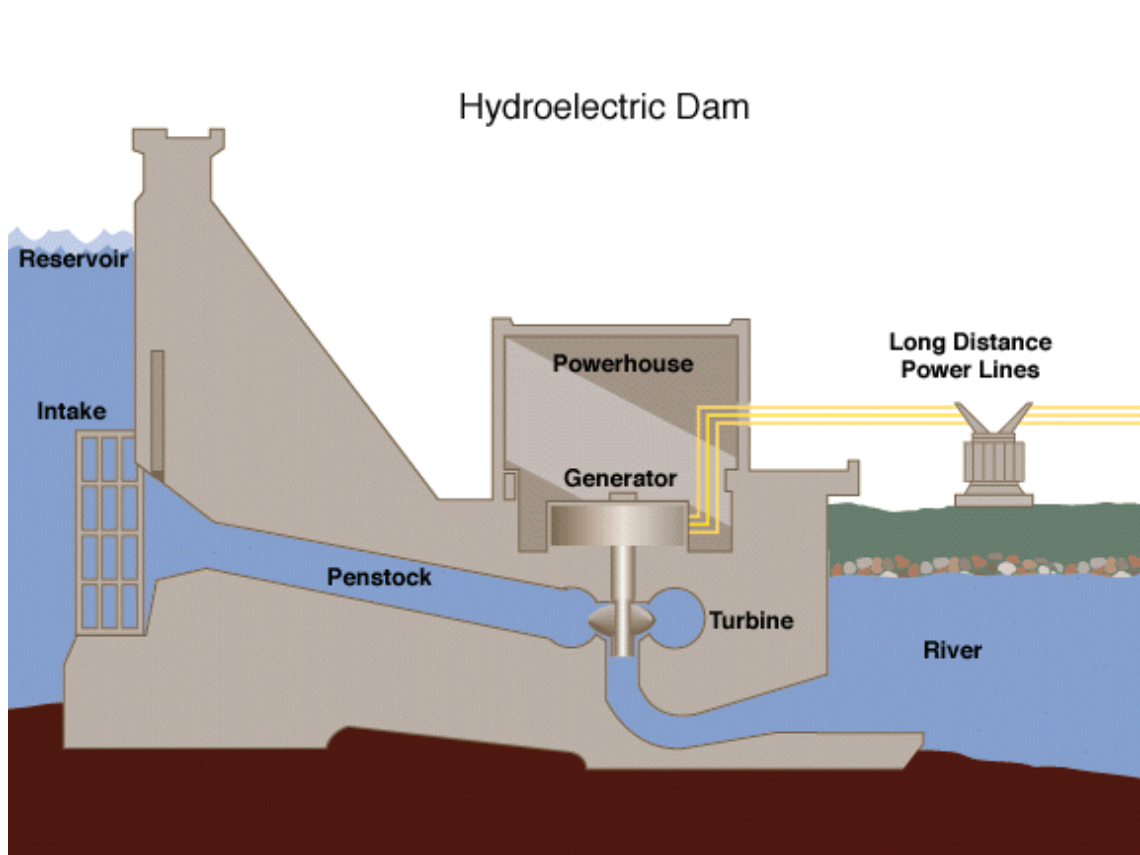


Figure 2.1.1. Overview of a general hydroelectric plant [16]

2.1.1 Kaplan Turbine

To give more understanding of the Kaplan turbine used in Hojum a brief description is first needed of the main types of modern turbines and the differences between them. There are two main types, impulse and reaction turbines, and the Kaplan belongs to the latter. What differs them a part is the way the energy conversion is carried out. In an impulse turbine water flows through a nozzle and hits the turbine. Thus, the energy flow is converted into kinetic energy which affects the turbine runner. In a reaction type turbine there are two types of energy conversions. First, the turbine is completely submerged in water, which creates a pressure drop between the inlet and the outlet that is converted into axial power, also called the reactive part. Secondly, impulse forces are created because of changes in velocity vectors when the water flows between the turbine blades. The most common reaction turbines used are Francis, Bulb and Kaplan, while the only impulse turbine really used today is the Pelton. For more information regarding the other types of turbines see [9] and [5].

Kaplan turbines are normally operating at a low head and high flow operations at relatively low RPM. Typical ranges are a head of 6-60 meters in fall head, 70-400 RPM and a production up to 200 MW of power. The size of Kaplan turbines varies

from two to eight meters in diameter and has four to eight runner blades.

A physical description of the Kaplan is given in Figure 2.1.2 below. A turbine runner with blades is attached to a shaft connected to the generator. Water enters the turbine via a spiral cone surrounding the turbine. The wicket gate is acting as a valve and controls the direction and size of the flow discharges Q [m^3/s] by adjusting the horizontal blades. When the waters has entered the inner parts of the turbine the vertical angle of the runner blades can be adjusted to deliver the maximum level of efficiency. These adjustable runner blades is the main difference between the Kaplan and other types of reaction turbines. Angles for the optimal efficiency when having a certain discharge are determined through experimental testing.

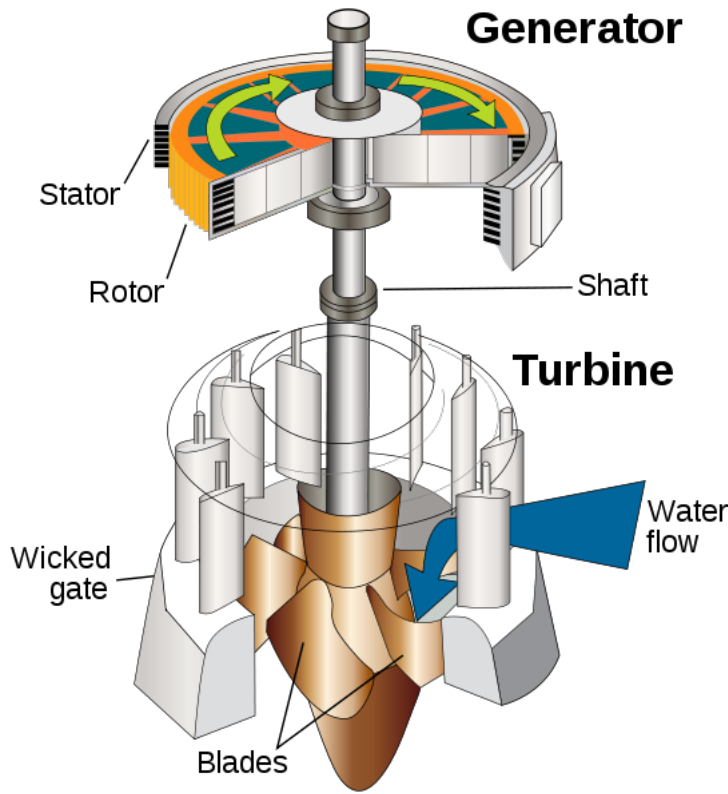


Figure 2.1.2. Kaplan Turbine[16]. Note that Wicked gate should be Wicket gate.

The mechanical power delivered by a turbine can be described as

$$P_m = Q\Delta p\eta = \omega T_m [W], \quad (2.1.4)$$

where Δp [Pa] is the pressure difference between inlet and outlet, η is the turbine efficiency, ω [rad/s] is the rotational speed and T_m [Nm] is the mechanical torque. This equation is essentially the same as Equation (2.1.3) expressed in different entities, Δp being interchangeable with $\rho g H_n$ [9].

2.1.2 Reservoirs, penstocks and outtake

A hydroelectric plant is usually located in the downstream of a body of flowing water, such as a river. A reservoir is not necessary but often constructed to create a buffer of energy, thus eliminating the dependency of a steady flow. The water conduit between the turbine and reservoir is called a penstock. It can vary in length from 20 to several thousands of meters and be in the form of open canals, tunnels, pipes or combinations and be constructed in several different materials such as wood, concrete or steel. The penstock is responsible for the major part of a hydroelectric plant system's dynamics.

When opening and closing the wicket gate it takes time for the body of water in the penstock to accelerate or decelerate and this may create pressure hammers or lag time in the system. Water elasticity may also have to be taken into account if the penstock is large enough. Depending on the design and material the penstock creates a loss in head due to friction and turbulence in the water. The connection between the reservoir and penstock is called a water intake, must be taken into consideration since it is a major source of turbulence and friction. The reason for this is mostly because of its design which often includes edges and a trash rack [5].

2.1.3 Generators

Synchronous generators are the main source of electricity in today's power systems. They operate in wind power plants, nuclear power plants, hydro power plants and many other types of power plants. In this section a description of how a synchronous generator works is given.

Physical description

Figure 2.1.3 shows a cross section of a three-phase synchronous machine with one pair of field poles. The machine consists of two essential elements: the armature and the field. The field is located on the rotor which is the rotating part of the generator connected to the shaft of for example a turbine on a hydro plant. The armature is located on the stator which is the static part of the machine. The armature and the field can also be fitted in opposite positions, but since the armature windings usually operate at a considerably higher voltage than the field windings and thus they require more space for insulation. The armature windings are also subject to much higher transient currents and must have sufficient mechanical strength. Therefore the normal case is to have the armature on the stator. The three-phase armature windings are distributed 120° apart from each other in space. This means that with uniform rotation of the magnetic field, the voltages produced in the windings will be displaced by 120° in the time phase.

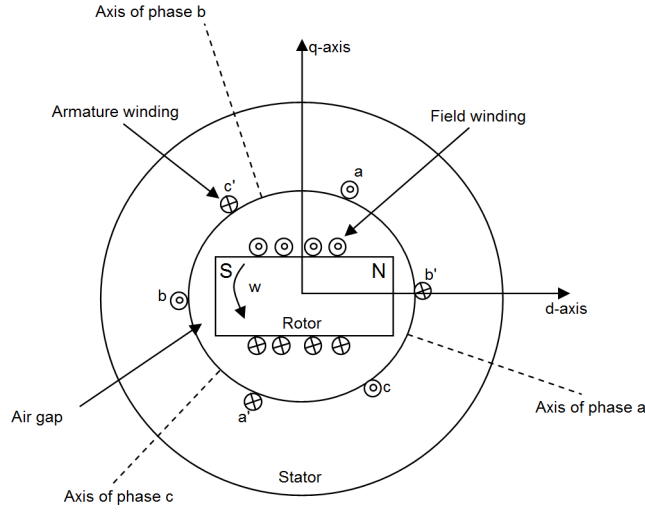


Figure 2.1.3. Schematic diagram over a three phase synchronous machine.

A direct current goes through the field windings and induces a magnetic field ϕ_r which induces alternative voltage(emf) E_r in the armature windings when rotating. This emf is 90° after the induced magnetic field ϕ_r (see Figure 2.1.4). The armature current I_a also induces a magnetic field ϕ_s , which has the same phase location as I_a . An equivalent circuit of one phase in the generator can be seen in Figure 2.1.5.

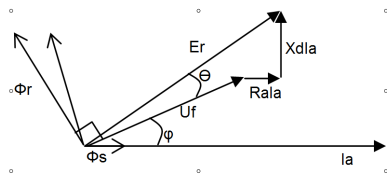


Figure 2.1.4. Phasor diagram.

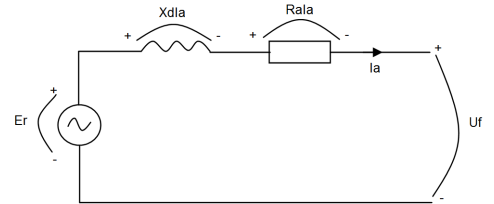


Figure 2.1.5. Equivalent circuit for one phase.

The field winding rotates with the rotor and in order to get a steady torque the fields of stator and rotor must rotate at the same speed. This speed is called synchronous speed. And is given by

$$n = \frac{120f}{P_f}, \quad (2.1.5)$$

where n is the speed in rpm, P_f is the number of filed poles in the stator and f is the frequency in Hz.

2.1.4 Strong grid and Island grid

The generator will be operating in two different settings, strong grid and island grid. Strong grid means that the generator is connected to a very big network, for example the entire network of Sweden, including many generators. Because of this the generator will not influence the frequency and the voltage of the strong grid. The generator will instead follow the strong grid's frequency and voltage. The power output from the generator to a strong grid can be set to a desired value. Island grid means that the generator is alone on the grid and thereby sets the frequency and voltage on the grid itself. This means that when a load change happens on the island grid it will effect the generator frequency and voltage. On the island grid the power output from the generator will be equal to what the island grid demands.

2.1.5 Governing a hydroelectric plant

The control system is a vital part of a hydroelectric plant. It is used for controlling and adjusting the total power output and leveling out fluctuations between the grid and plant with respect to power and frequency. A. Kjolle [9] describes this by expressing two major purposes for turbine governors:

1. "To keep the rotational speed stable and constant of the turbine-generator at any grid load and prevailing conditions in the water conduit"
2. "At load rejections or emergency stops the turbine admission have to be closed down according to acceptable limits of the rotational speed rise of the unit and the pressure rise in the water conduit."

In a plant with a Kaplan turbine these goals are achieved by controlling the closing and opening rate of the turbine wicket gate. Thus, controlling the water level in the reservoir to maintain desired head. Note that the adjustable runner blades in the Kaplan turbine can used to directly control the plant but in this case are there to achieve maximum efficiency. In Figure 2.1.6 a general schematic of a typical control system is shown.

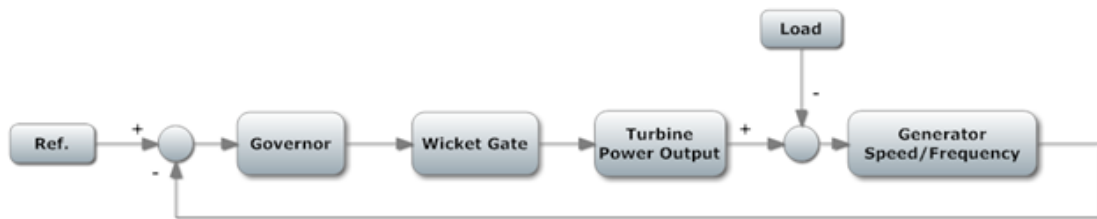


Figure 2.1.6. Generic control system in a hydroelectric plant

As can be seen above in Figure 2.1.6 the governor responds to the error between the reference and the current output from the generator. The set point and feedback does not have to be the frequency, it can also be power or load output. A typical step response of a governor and a plant when a load reduction is carried out can be seen below in Figure 2.1.7. The dynamics of the plant are such that when there is a load reduction the rotational speed or frequency will increase due to the decrease of power demanded on the grid (see Figure 2.1.5). A governor will then react to the error between the reference and feed back and thus closing the wicket gate until the deviation is eliminated. If a load increase is performed the opposite will occur, i.e. a decrease in rotational speed and an increase in torque.

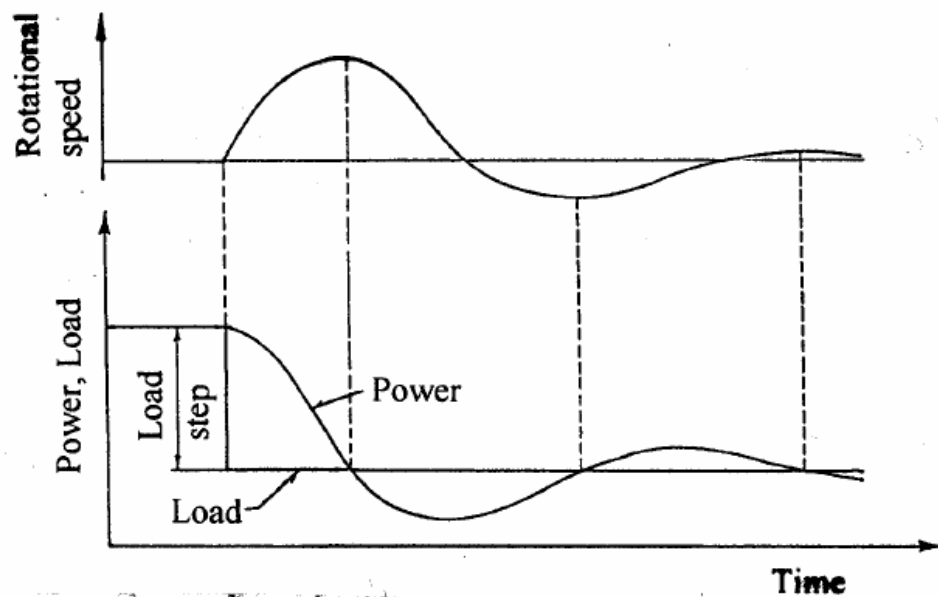


Figure 2.1.7. Description of a system response when a load reduction is performed [9]

2.2 Overview of Modeled System

This section concerns the system modeled. First a brief description of the Hojum hydroelectric plant in Trollhättan, which is the basis of design for the test bench model, followed by an overview of the parts being modeled.

2.2.1 Hojum, Trollhättan

The Hojum plant consist of three power units; G14, G15 and G16, all Kaplan type turbines. The first two was put into operation 1942 and G16 during 1992. In 2008 the G15 unit was renovated and both turbine and generator were replaced. The system modeled is based on the design and values from of the G15-unit to the largest extent possible. Below, in Figure 2.2.1, and a Table 2.1 a schematic and table with rated values can be seen [15].

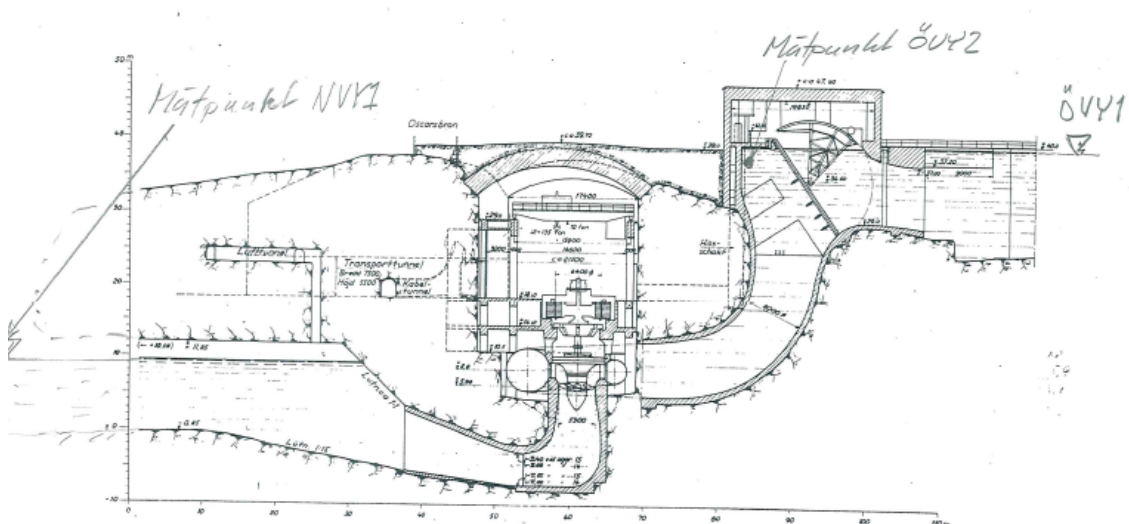


Figure 2.2.1. The Hojum G15 unit [14]

Turbine	Kaplan with 6 runner blades
Diameter	5.3 m
Rated Head	31 m
Maximum Discharge	$221 \text{ m}^3/\text{s}$
Maximum Measured Power Output at 31m head	58 MW
Rated Generator Power	66 MW
Rated Speed	136.4 rpm

Table 2.1. Rated values of Hojum G15 [14].

2.2.2 Modeled System

The concept drawing of the system below (see Figure 2.2.2), together with Figure 1.1 gives an overview of the system that is modeled and the parts involved. As can be seen the plant is divided into two main parts regarding the physical modeling; a process and an electrical part. The two sub-systems are connected via a governor and transfer of entities between the models.

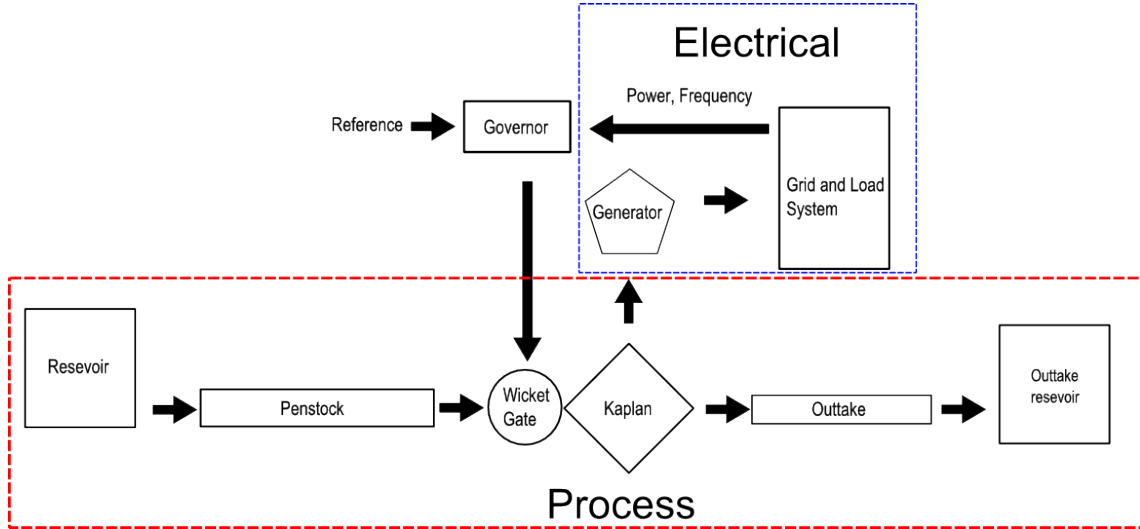


Figure 2.2.2. Sketch of modeled system.

2.3 Process Modeling

Here follows the modeling of the process part of the plant. The modeling has been divided into the following independent sub-models of the plant:

- Reservoir and Outtake Reservoir
- The penstock and outtake
- Wicket Gate
- Kaplan Turbine

All of the sub-models have two things in common. The first is the principle of mass conservation. Mass conservation can be expressed as

$$\frac{dM}{dt} = \dot{m}_{in} - \dot{m}_{out}, \quad (2.3.1)$$

where M [kg] is the total mass contained in the volume and \dot{m}_{in} [kg/s] and \dot{m}_{out} [kg/s], respectively, are the mass flow rates. Second is a given pressure drop p_{drop} [Pa] at any time in the model, which is a function of the flow $p_{drop} = f(Q)$ [4, 1].

2.3.1 Reservoir and outtake reservoir

The reservoir is considered to have the form of a basic cylinder with the height h [m], constant diameter D [m] and area A [m²]. For a volume with a constant cross section the water level is given by the volume balance

$$\frac{dh}{dt} = \frac{1}{A}(\dot{Q}_{Outflow} - \dot{Q}_{Inflow}). \quad (2.3.2)$$

Bottom pressure p_{bottom} [Pa] is then

$$p_{bottom} = \rho gh. \quad (2.3.3)$$

The outflow from the reservoir to a connected penstock is modeled as a pressure loss due to friction, which can be formulated as [6].

$$p_{drop} = K_{outflow} \frac{\rho}{2} v^2 \quad (2.3.4)$$

Where $K_{outflow}$ is a constant of the friction from the exit of the reservoir and v is the velocity of the water. The total pressure transferred to the penstock then becomes

$$p_{in} = p_{bottom} - p_{drop} \quad (2.3.5)$$

An outtake reservoir is modeled as a reservoir with a very large diameter, hence $\frac{dh}{dt} \approx 0$.

2.3.2 Penstock and Outtake

The penstock is a major contributor to the dynamics in a hydroelectric plant. The dynamics are described with the help of the principle of conservation of momentum [4]

$$\frac{dG}{dt} = \dot{m}_{in}v_{in} - \dot{m}_{out}v_{out} + (A_{in}p_{in} - A_{out}p_{out}) - F_f + A\rho g\Delta h, \quad (2.3.6)$$

where

- G is the momentum in the volume $[kgm/s]$
- $v_{in/out}$ is the velocity at the inlet and outlet of volume $[m/s]$.
- $A_{in/out}$ is the area at the inlet and outlet of volume $[m^2]$.
- F_f is the friction force $[N]$.
- Δh is the difference in height between inlet and outlet of volume $[m]$.
- \dot{m}_{in} and \dot{m}_{out} is the change in massflow at inlet and outlet. They are calculated numerically by Dymola in each step of the simulation.

The friction force F_f is dynamical and varies depending whether the flow throughout the pipe is laminar or turbulent. The loss of friction in a pipe can be described as [6]

$$F_f = p_{loss}A, \quad (2.3.7)$$

where $p_{dropPipe}$ is the pressure drop or head loss due to friction in the pipe and A $[m^2]$ is the area of the pipe. The drop in pressure is described as

$$p_{dropPipe} = \lambda \frac{L}{D} \frac{\rho}{2} |v|^2, \quad (2.3.8)$$

where

L is the length of the pipe, D the diameter, $|v|$ fluid velocity and λ a friction factor depending on the Reynolds number

$$Re = \frac{|v| D}{\nu} \quad (2.3.9)$$

with ν $[\frac{kg}{sm}]$ being the kinematic viscosity of water.

It is the Reynolds number determines the type of flow

- If $Re < 2000$ then the flow is *laminar*. Then [5]

$$\lambda = \frac{64}{Re}. \quad (2.3.10)$$

- If $Re > 4000$ then the flow is *turbulent*. Then λ is approximated to

$$\lambda = 0.364 * Re^{-1/4}, \quad (2.3.11)$$

according to [4] and [6].

2.3.3 Wicket Gate

The wicket gate is modeled as a valve [1]. A fully opened valve can be expressed as

$$Q = K_v \sqrt{p_{drop}}, \quad (2.3.12)$$

where $K_v[m^3/h]$ is how much that flows through the valve per hour at a specific opening. K_v is dependent on the valve position x that ranges from 0 to 1.

The valve is modeled with first order dynamics to represent a lag time when closing and opening the valve:

$$\frac{dx}{dt} = \frac{1}{\tau}(x_{input} - x_{current}). \quad (2.3.13)$$

The time constant τ is the time it takes for the valve to open 63 %.

2.3.4 Kaplan Turbine

The mechanical power from a Kaplan turbine is [9]

$$P_t = Q p_{drop} \eta_t, \quad (2.3.14)$$

where Q is the flow p_{drop} , is the drop in pressure from turbine inlet to turbine outlet and η_t the current turbine efficiency.

η_t depends on two factors, the flow through the turbine, and the angle of the runners blades. The deviation from the maximum efficiency at a certain flow is called the combination error. Data for the combination error is gathered through turbine testing. Data has been available throughout this project and thus η_t is modeled as a function of the flow and runner blade angle α i.e.

$$\eta_t = f(Q, \alpha) \quad (2.3.15)$$

or by a look up table

$$\eta_t = \begin{array}{c|cccc} & \alpha_1 & \alpha_2 & \cdots & \alpha_j \\ \hline Q_1 & \eta_{t11} & \eta_{t12} & \cdots & \eta_{t1j} \\ Q_2 & \eta_{t21} & \eta_{t22} & \cdots & \eta_{t2j} \\ \vdots & \vdots & \vdots & \ddots & \\ Q_i & \eta_{ti1} & \eta_{ti2} & & \eta_{tij} \end{array} \quad (2.3.16)$$

Together with Equation (2.1.4) the mechanical torque T_m [Nm] generated is

$$T_m = \frac{Qp_{drop}\eta_t}{\omega_s}, \quad (2.3.17)$$

where ω_s [rad/s] is the synchronous speed of the generator.

2.4 Electrical Modeling

This section includes the model equations for a synchronous generator of third order, description of load model and slack model.

2.4.1 Modeling of synchronous generator

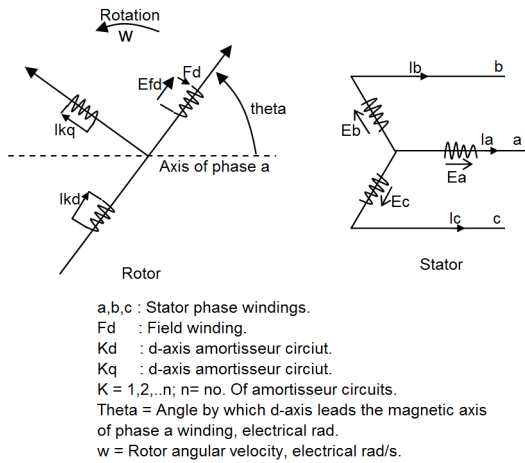


Figure 2.4.1. Rotor and stator circuits of a synchronous machine.

2.4.2 The DQ-transformation

When studying electric machines it is preferable to transform the regular three phase system to an equivalent two phase rotating coordinate system called the dq-system [7]. d and q are two fictitious axes perpendicular to each other located on the rotor (see Figure 2.4.1) that rotates with the same speed as the magnetic field in the machine. The transformation is made in two steps: 1) A transformation from the three-phase stationary coordinate system to a two phase stationary coordinate system called the $\alpha\beta$ -system. 2) A transformation from the $\alpha\beta$ -system to the dq rotating system. A three phase system consists of the following voltages:

$$V_a(t) = \hat{V} \sin(\omega t + \theta), \quad (2.4.1)$$

$$V_b(t) = \hat{V} \sin(\omega t - \frac{2\pi}{3} + \theta), \quad (2.4.2)$$

$$V_c(t) = \hat{V} \sin(\omega t - \frac{4\pi}{3} + \theta), \quad (2.4.3)$$

These three voltages can also be expressed as a space vector:

$$V_s = \frac{2}{3} K [V_a(t) + e^{j\frac{2\pi}{3}} V_b(t) + e^{j\frac{4\pi}{3}} V_c(t)], \quad (2.4.4)$$

K is a scalar constant. V_s can also be expressed as a real and imaginary part:

$$V_s = V_\alpha + jV_\beta, \quad (2.4.5)$$

This makes it possible to express the transformation from the three phase system to the two phase system called the $\alpha\beta$ -system.

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = K \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} \quad (2.4.6)$$

The next step is to describe V_s in coordinate system that rotates with the speed ω , that is the dq-system:

$$V_{dq} = e^{-j\theta} V_s = V_d + jV_q, \quad (2.4.7)$$

where

$$\theta = \omega dt. \quad (2.4.8)$$

The last transformation is made from the $\alpha\beta$ -system to the dq-system:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix}. \quad (2.4.9)$$

2.4.3 Per-Unit system

All the generator and network models are in per-unit, which means that all the values are normalized to a common MVA base. This is standard practice in power system analysis and usually the generator parameters are given in per-unit from the manufacturer. By normalizing for example the generator equations it will be easier to understand the generator performance due to that the parameters will be of same type. The per-unit value is calculated in the following way[11]:

$$PerUnit_{value} = \frac{actual_{value}}{base_{value}} \quad (2.4.10)$$

2.4.4 Third order model of synchronous generator

The transformation from the normal three phase system to the dq-system enables a model (see Section 2.4.5) to be built were the equations are written in the dq coordinate system. A model of third order was chosen, and a number of assumption must be made for the model to work:

1. The three-phase stator windings are symmetrical.
2. The capacitance of all windings can be neglected.
3. Each of the distributed windings may be represented by a concentrated winding.
4. The change in the inductance of the stator windings due to rotor position is sinusoidal and does not contain higher harmonics.
5. Hysteresis loss is negligible but the influence of eddy currents can be included in the model of the damper windings.
6. In the transient and sub-transient states the rotor speed is near synchronous speed.
7. The magnetic circuits are linear (not saturated) and the inductance values do not depend on the current.

Worth mentioning is that there are higher order generators models. What differs between the models is how many transient states in the circuits you want to study. In this paper a third order model was chosen to be sufficient, but the model can easily be expanded to include more transient states. Figure 2.4.2 corresponds to the different transient states for q and d-axis. The transient states are due to that in the transient periods the armature flux is forced to paths outside the field windings by currents that are induced in the field windings, the armature flux have both d and q-components. The flux path is distorted by the d-axis field current and by q-axis

rotor body currents. Each of the transient EMF's have a time constant which is the time it takes for the magnetic energy stored in the winding to decay to 0 (steady state) [11].

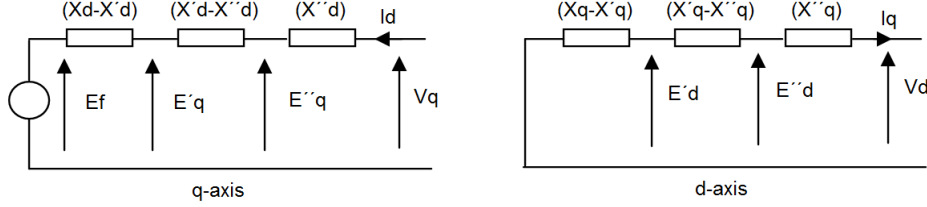


Figure 2.4.2. Generator equivalent circuits for q and d-axis with resistance neglected[8].

2.4.5 Model equations

2.4.5.1 Voltage equations

$$V_d = -r_a I_d - X_q I_q \quad (2.4.11)$$

$$V_q = E'_q + X'_d I_d - r_a I_q, \quad (2.4.12)$$

where r_a is the armature resistance, X_q is the Q-axis synchronous reactance, X'_d is the D-axis transient reactance, E'_q is the Q-axis transient emf, V_d is the voltage in d-axis and V_q is the voltage in q-axis (see Figure 2.4.2) [11].

2.4.5.2 Swing equations

The swing equations describe the mechanical behavior of the generator:

$$\dot{\omega} = \frac{1}{2H} (P_m - P_e - D(\omega - 1)), \quad (2.4.13)$$

$$\dot{\delta} = 2\pi 50 (\omega - 1), \quad (2.4.14)$$

$$P_e = E'_q I_q + (X'_d - X_q) I_d I_q, \quad (2.4.15)$$

where ω is the rotor speed, P_m is the mechanical power from the turbine, P_e is the electrical power out from the generator, D is the dampening coefficient, δ is the rotor angle and H is the inertia constant for generator and turbine [11].

2.4.5.3 Transient EMF equations

The transient EMF equation describes the behavior of the magnetic flux in the q-axis winding:

$$T'_{d0} \dot{E}'_q = E_{fd} - E'_q + I_d(X_d - X'_d), \quad (2.4.16)$$

where T'_{d0} is the D-axis transient time constant and E_{fd} is the field current set by the voltage controller (see Section 2.5.2) [11].

2.4.5.4 Generator parameters

The following parameters were used in the generator model, which is taken from the data from G15 Hojum (see Appendix 1.2):

Parameter	Value	Description
S_n	66 MW	Rated power
U_n	11.3 kV	Rated voltage
X_d	1.041 pu	D-axis synchronous reactance
X_q	0.651 pu	Q-axis synchronous reactance
X'_d	0.3 pu	D-axis transient reactance
H	9	Inertia constant
D	0	Dampening coefficient
r_a	0	Armature resistance

Table 2.2. Generator parameters.

2.4.6 Load model

The load model is a constant PQ load which means that the load draws a constant P (active power) and a constant Q (reactive power) from the network. Through parameters in the model the amount of active and reactive power is set. Also a third parameter is connected to the model that makes it possible to change how much of the load is used. The interval is set to 0-100% and this parameter is controlled via the interface in LabVIEW. This makes it possible to make load changes in real time and see how the generator reacts.

2.4.7 Slack model

The slack model is used to imitate the behavior of a strong network, e.g. the whole power grid of Sweden. The Slack node can be seen as a generator with constant

voltage and constant frequency and when this node is connected to the grid it acts as a reference to other generators on the grid. The Slack model is connected to the grid when the model is running on a strong grid.

2.5 Control Theory

In this section the control theory of the hydro power plant will be described. There are three control loops that controls the power plant:

- Frequency control that controls the rotor speed in the generator and hence the frequency of the grid.
- Voltage control that controls the field current in the generators rotor which affects the voltage output from the generator.
- Water level control that controls the water level in the reservoir through dam hatches.

The type of controller that are used for these control applications are PID controller. PID stands for proportional-integral-derivative and is a widely used controller in industrial control systems. A PID controller calculates an error between the set-point value $r(t)$ (the preferred value in the process) and the process value $y(t)$ (the actual value of the process) (see Figure 2.5.1). The controller then tries to minimize the error through a control algorithm that contains the three parts P, I and D. The P part depends on the present error, I part accumulates past errors and D depends on the rate of changes in the error. The sum of these three values then becomes the control signal $u(t)$ that adjusts the process so that eventually, with the right parameter values, the error $e(t)$ converges to 0.

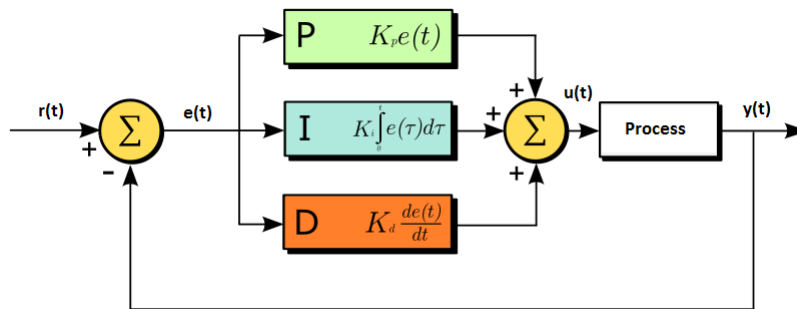


Figure 2.5.1. Block diagram over PID controller[9].

2.5.1 Frequency control

The frequency of the generator depends on the rotor speed. To get the right frequency the generator must rotate at synchronous speed. The speed of the generator depends on the water flow through the turbine. Hence, to be able to control the speed of the generator the water flow through the turbine is controlled by a hatch. The input to the generator model is the mechanical power of the turbine P_m (see Equation (2.4.13)) that depends on the flow.

The frequency controller is a PID controller, the set-point value $r(t)$ constitutes of the preferred frequency and the measured value $y(t)$ is the actual frequency. Through the error $e(t)$ a control signal $u(t)$ is calculated that controls the valve position of the wicket-gate (see Section 2.3.3). The wicket-gate controls the water flow into the turbine. The control signal is constrained the values between 0 and 1, which means that at 0 the hatch is closed and at 1 the hatch is completely open.

2.5.2 Voltage control

The output voltage from the generator is controlled by the field current in the rotor windings and is controlled by an PID controller. The set-point $r(t)$ is the preferred voltage output and the process value $y(t)$ is the measured voltage on the stator. The output from the controller is the field current for the stator-winding E_{fd} .

2.5.3 Reservoir Level Control

In smaller reservoirs it is possible to control the water level via extra dam hatches so that water is by-passed the turbine and power unit. The set-point $r(t)$ becomes the preferred water level and the process value $y(t)$ is the measured water level. The control signal $u(t)$ controls the extra dam hatches to get the preferred water level in the reservoir.

3 IMPLEMENTATION

This chapter concerns the implementation part of the modeling in Chapter 2. It begins with a description of the tools that have been used and then follows the implementation of the physical model, construction of GUI, design of control sequences and how to establish communication.

3.1 Software and Communication Protocols

Below follows a short descriptions of the various software and communication protocols used.

3.1.1 Dymola

All the models are made in Dymola which is an object oriented graphical simulation program that uses the simulation language Modelica. Dymola is an equation-based simulation tool unlike block-oriented tools such as Simulink. In Dymola you can both use graphical code and also manually entered row-based code. If graphical code is used Dymola will convert all the graphical code into Modelica code before simulation. The simulation environment is divided into two parts: the modeling part and the simulation part. The modeling part is where you draw the models and check them regarding to syntax and structure. In the simulation part the code is first converted into C-code and then simulated. In the simulation editor it is possible to look at plots of all variables in the model. An example of a model in Dymola is showed in Figure 3.1.1 where a graphical view of the model is showed in the left window and the simulation tool is showed in the right window [2].

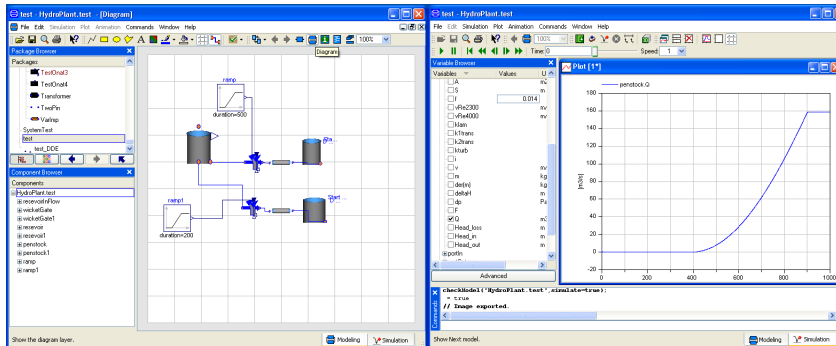


Figure 3.1.1. Modeling window(left side) and Simulation window(right side).

3.1.2 LabVIEW

LabVIEW 8.2 has been used to create the graphical user interface (GUI) and for implementation of the control sequences.

LabVIEW is a software programming tool developed by National Instrument. It uses a high level graphical programming language which resembles flow charts. Programs are executed by the way graphical blocks in a program are connected. A program in LabVIEW is called a VI or *virtual instrument* and contains an interface view and a graphical programming view. The user can create standard and custom graphical components in the interface view and connect them in the programming view, thus enabling a relatively simple and fast way to design a GUI. The LabVIEW standard library is extensive and has a lot of modules for network support, such as the OPC protocol.

3.1.3 TOP Server

Top Server is an OPC Server and HMI (human machine interface) connectivity developed by Software Toolbox, North Carolina, USA. It works as a native OPC server which is a bridge to multiple non-OPC communication protocols, such as DDE (see below). This means that you can establish communication between two platforms that uses two different protocols.

3.1.4 Communication Protocols

OPC

OPC stood for OLE (Object Linking and Embedding) for Process Control but is now to be associated with “open connectivity via open standards”. It was developed by an industry collaborative task force in 1996, and the goal was to create a standard within industry automation. Later the OPC Foundation was founded and took over the responsibilities of further developing and maintaining the standard. For further and more detailed information regarding the OPC standard and the OPC foundation visit www.opcfoundation.org.

DDE

Dynamic Data Exchange (DDE) is a protocol to enable data transfer across Windows based programs using the native messaging function between applications in Windows. It is an old technology that has been phased out by newer technologies such as netDDE but is still used today in various applications, such as Dymola. The application that sends data through DDE acts as an DDE-server.

3.2 Physical Model

The physical model of the hydroelectric plant is modeled in Dymola using components in Chapter 2. It is divided into an electrical part and a process part of the plant. In Figure 3.2.1 below an overview of the implemented model can be seen. Since Dymola is object oriented all the separate sub-models and systems have been developed as independent classes. Thus it is relatively easy to create new scenarios and variations of the physical model. Classes in the model are connected to each other through a basic Dymola class called *Connector*. A connector is able to work as a communication port and transfer entities from one model to another.

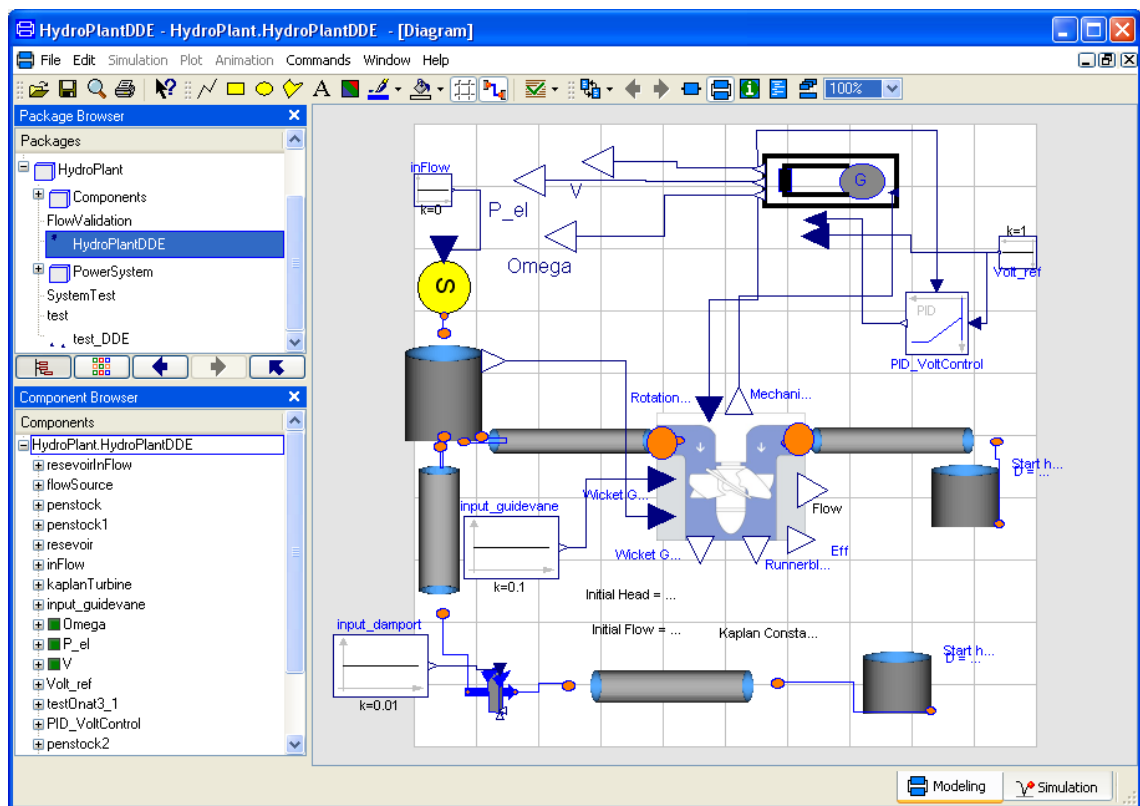


Figure 3.2.1. Graphical overview of the model implemented in Dymola

The standard library in Dymola has been used to the largest extent possible for the project, this including mathematical operations, values of constants and so forth. External inputs are done by having constant signals connected to an inport in a Dymola model. Out ports can be read externally directly.

3.2.1 Process

The process part of the model is implemented in Dymola with the components in the list below. Connectors in the process part are called *flow ports* and carry information

about pressure and mass flow rate through connected parts in the system.

- *Reservoir*. Works both as the dam reservoir and outflow area. Calculations of bottom pressure, water level and friction losses due to the outlet and inlet are calculated in this class. A reservoir has one flow connector for water flowing in to or out of to the reservoir. The dam reservoir is an altered version of the basic reservoir such that it has extra connectors for additional outflow due to level control dam hatches and additional inflow.
- *Penstock*. The penstock is where water friction losses and momentum balance are calculated. Main parameters are length, diameter and it uses two flow connectors.
- *Wicket Gate*. Used to simulate the guided vanes in the plant. It has a input port which range from a value of 0 to 1 and an outport which gives the current position of the gate. Depending on the input, pressure loss and flow throughput are calculated. A Wicket Gate class with different input parameters is used to simulate the emergency dam hatches.
- *Kaplan Turbine*. Contains the *Wicket Gate* model. It has several inports and outports, the in ports are wicket gate input, actual head for calculation of efficiency and rotational speed determined by the generator. The outports are efficiency, runner blade and wicket gate angle, flow in turbine and finally the mechanical torque generated which is connected to the generator. Calculations performed in the class are the flow throughout the turbine, mechanical power generated, losses due to friction, angle of runner blades and corresponding efficiency factor.

3.2.2 Electrical

The electrical part of the Dymola model consists of a generator of 3rd order, a Slack node and a load. The model is made so that it can either be run in an island network, where only the generator is connected to the load, or in strong network where both the generator and the load are connected to a Slack node that acts as a voltage and frequency reference. Included in the model is also the voltage controller for the generator that controls the field current in the generator. The electrical model inputs are Pm, Loadstep and BreakerSignal see Figure 3.2.2. Pm is the mechanical power from the turbine that drives the generator model (see Equation(2.4.13)). Loadstep is a parameter that is set in LabVIEW and determines how much of the load that used. BreakerSignal closes and opens the breaker. The outputs from the model are V, Pe, and ω . V is the phase voltage of the generator, Pe is the electrical power that the generator produces to the network and ω is the rotational speed of the generator, which also decides the frequency. ω is also fed back to the turbine model because the generator shaft is connected to the turbine and runs on the same rotational speed. The slack node is connected via a breaker that makes it possible to connect

and disconnect the load and the generator in real time to imitate a connection to a strong grid. The breaker signal is controlled from the LabVIEW interface.

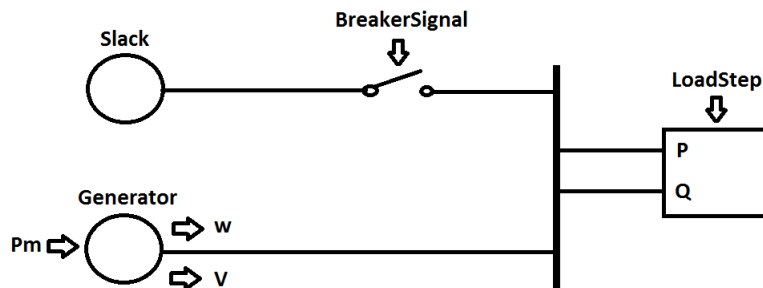


Figure 3.2.2. Schematic picture over the electric Dymola model.

3.3 Interface and Control Sequences

The interfaces have been constructed by the standard components in LabVIEW 8.2. Figure 3.3.1 shows an overview of the program structure and is best described by the following:

- When the program initializes data sockets are opened and communication is established. The Dymola init-file is read so simulation parameters can be changed if necessary.
- When the simulation is started the program enters the main loop. Here read/write operations are performed, graphs are updated, control sequences performed and so forth.
- If the simulation is turned off, the program exits the main loop and closes data sockets.

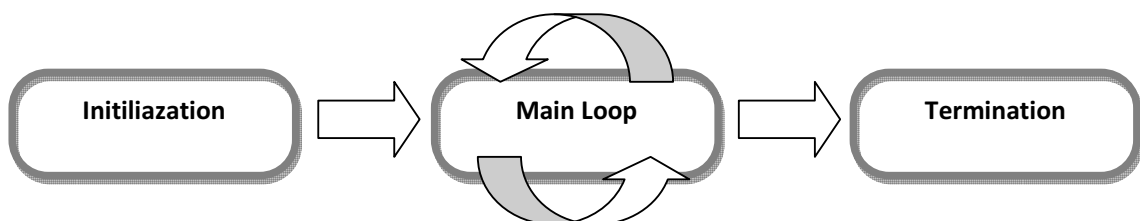


Figure 3.3.1. Program structure in LabVIEW.

Figure 3.3.2 below shows an extract from the implemented program in the LabVIEW block view.

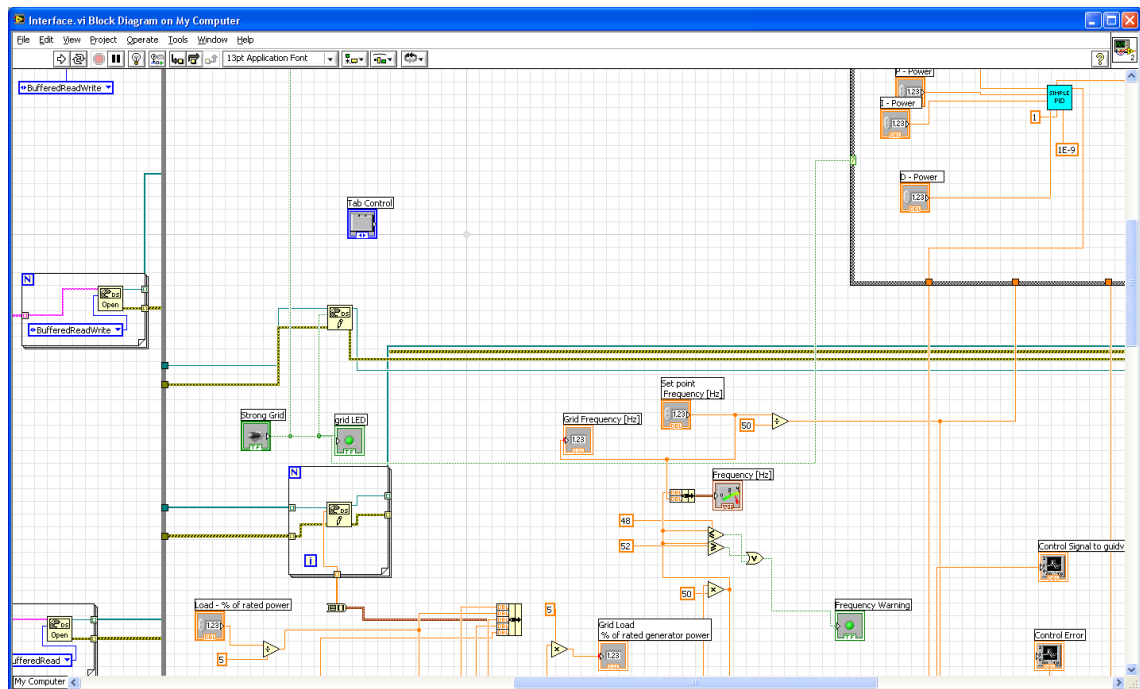


Figure 3.3.2. Extract from the block view in LabVIEW to demonstrate how the implementation looks like.

There are no control theory components, such as PID controllers, included in the 8.2 standard library. However National Instrument developer zone have demos available free of use demonstrating how to implement generic PID controllers with the components available. The controllers in this project are based on designs in these demos, however they are altered to fit this projects specific needs. Figure 3.3.3 below shows an example of a PI controller used for level control in LabVIEW.

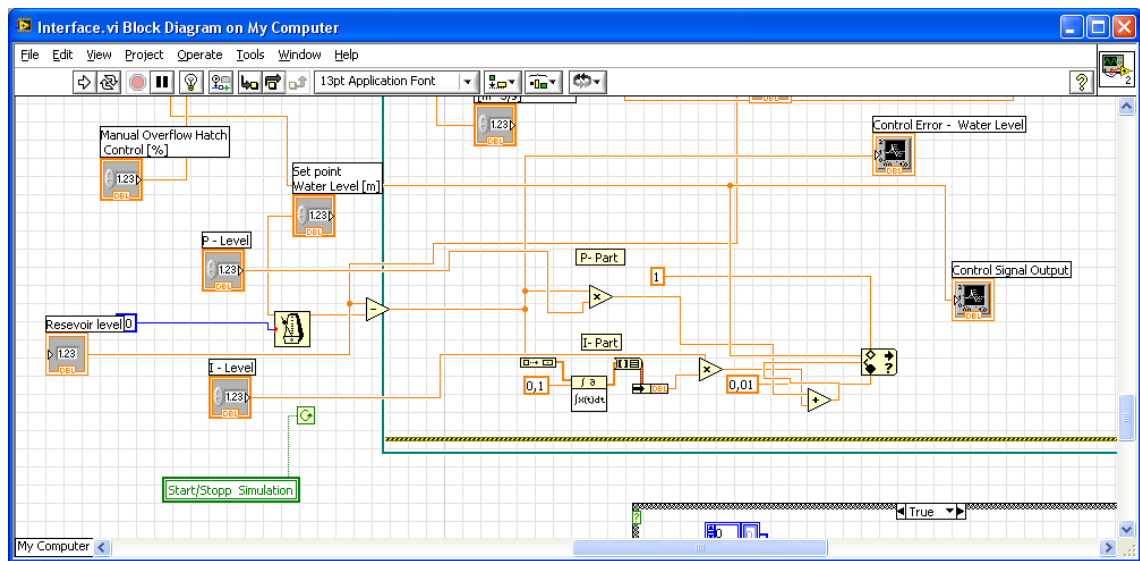


Figure 3.3.3. Implementation of a PI type controller in LabVIEW.

3.4 Communication

To establish communication between the model in Dymola and the interface in LabVIEW, TOP Server is used. The general principle for connecting the programs can be seen in Figure 3.4.1 below.

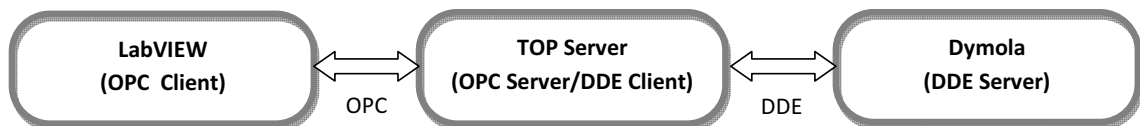


Figure 3.4.1. Communication between LabVIEW, TOP Server and Dymola.

Dymola has a built in support for DDE communication via Dymosim, which is an executable file generated when compiling the model. Dymosim has a built in DDE-server and creates tags and addresses based on name of components in the model.

In LabVIEW the DataSocket component in the standard Library is used. How to establish read and write functionality between LabVIEW and an OPC server can be seen in Figure 3.4.2.

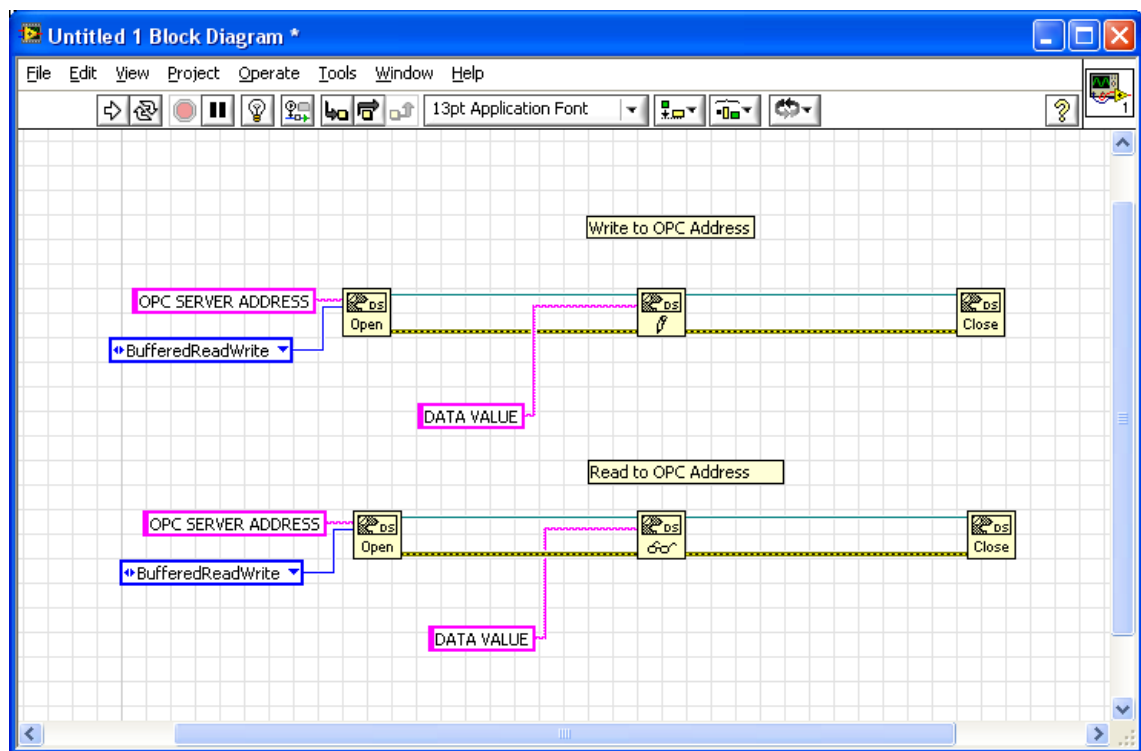


Figure 3.4.2. How to write and read from OPC addresses using the built in data sockets in LabVIEW.

Appropriate sampling rates in the system are decided through testing and tuning.

4 SIMULATION AND RESULTS

4.1 Validation and Verification

Below follows a description of how the verification and validation is performed and the result of it. Note that in the graphs taken from LabVIEW, the X-axis is not real time but number of samples in LabVIEW. One sample equals 0.02 seconds.

4.1.1 Verification

The verification of the model and interface is done by testing different scenarios and investigate if they respond as desired. The procedure took place in the following way:

- *Test of model and sub-models in Dymola.* Besides standard compilation in Dymola of the components each one was tested individually by setting up different test scenario and then examining that desired entities are transferred through the system. For example one test consisted of two reservoirs connected with a pipe. It was examined if flow and pressure was transferred through the system and that the water levels leveled out. Similar tests were conducted on all components in the system.
- *LabVIEW program.* In LabVIEW the verification procedure was to run the program and see that the interface compiled and the controls gave the correct results.
- *Communication.* The verification of the communication between LabVIEW and Dymola was done in TOP Server. Signals were sent from LabVIEW and it was verified in TOP Server that the Dymola model registered them.

The final physical model passed all the above steps of verification.

4.1.2 Validation

There are three stages of validation. In the first, the test bench is compared to existing theory regarding hydroelectric plants and similar works, in the the second the output is compared to data obtained from the Hojum plant [14] and the third is a comparison of the output against another simulation software, Simpow.

Validation against theory

First the data is compared to the theory in Section 1.1.4. regarding load reduction and increase. It can be seen in Figure 4.2.3 that the model behaves as it should with an increase and decrease in frequency for respective case. When the wicket gate is opened, the power output increases (see Figure 4.1.1) and there is a pressure drop in the turbine due to the acceleration of water, this agrees with statements in [5].

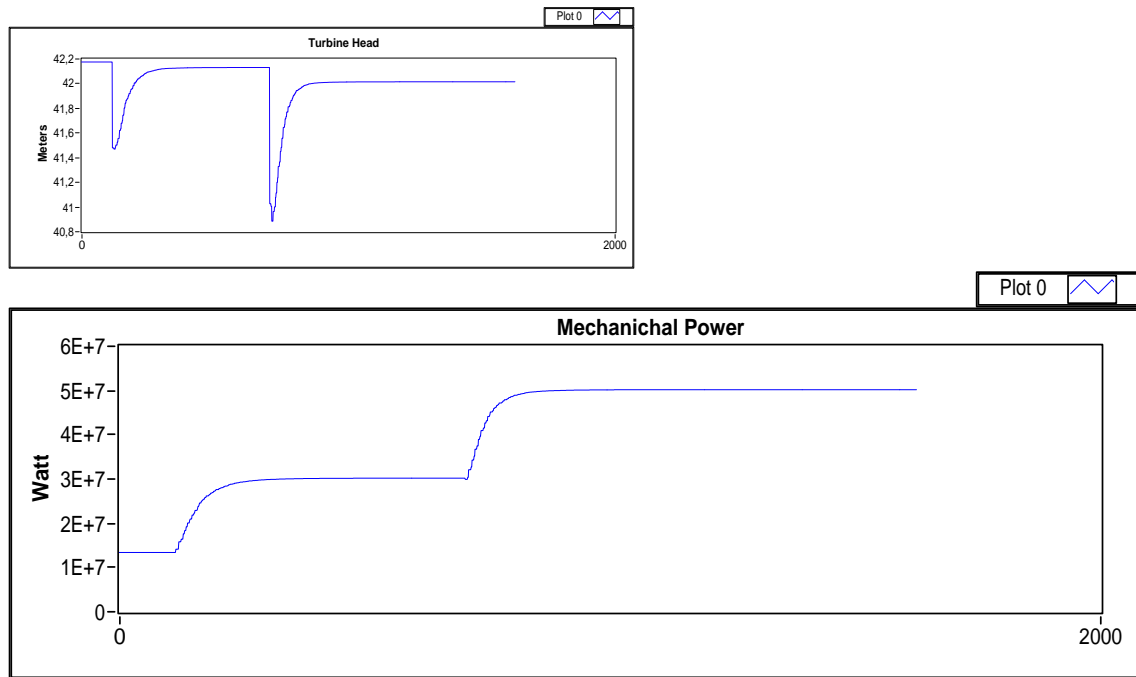


Figure 4.1.1. Pressure drop in turbine due increasing power output. The top graph shows the head loss when there is an increase in power in the lower graph. The turbine head loss corresponds to a drop in frequency on the generator.

Comparing the output with the results of a similar master thesis by Gustav Holmquist [8] (see Figure 4.1.2) also confirms the dynamic behavior of the model. There is a frequency drop when there is a power increase. Note that this test does not consider the numerical values of the results, only the behavior of the dynamics.

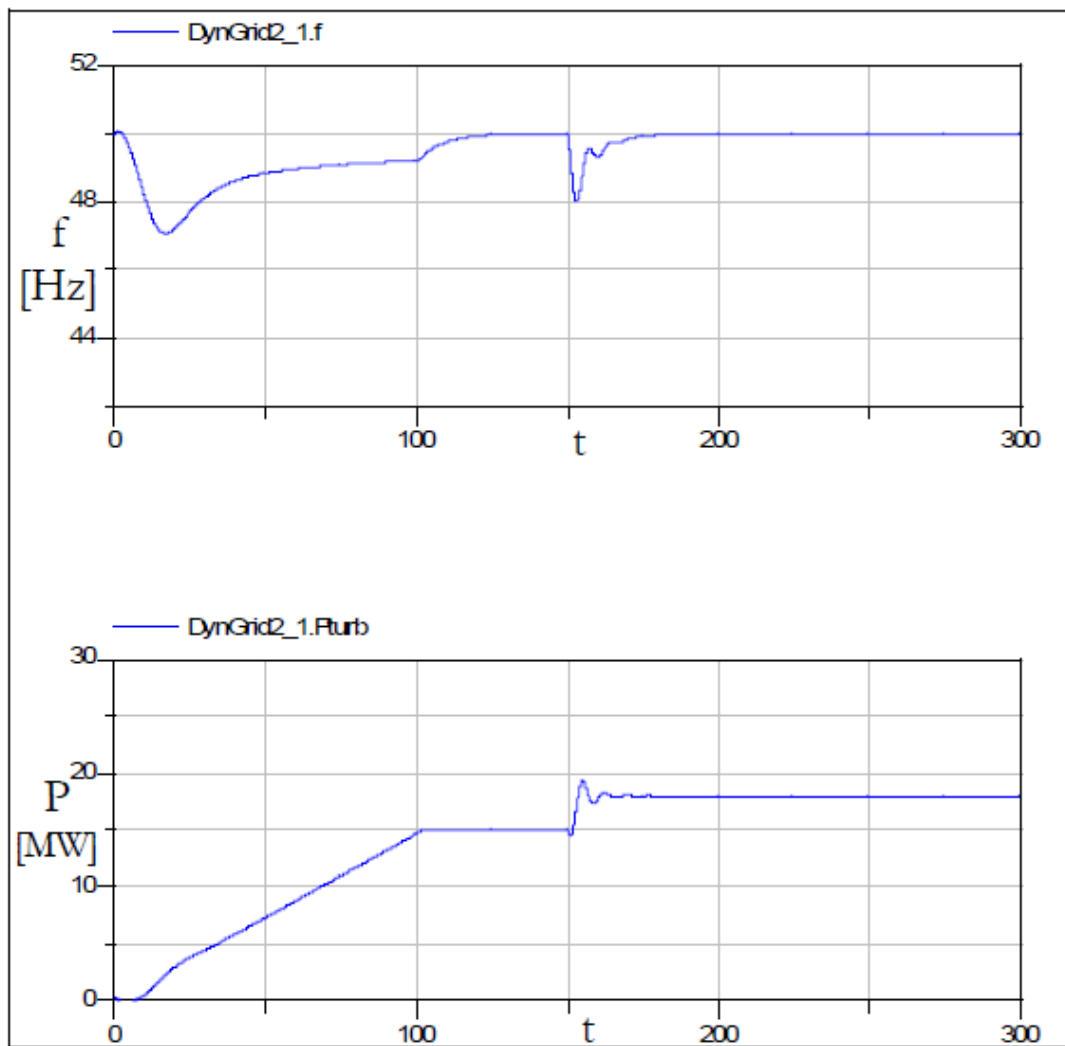


Figure 4.1.2. Similar dynamic behavior in frequency drop was achieved in another master thesis by Gustav Holmquist [8].

Validation against Hojum

A test versus data obtained from [15] was performed. In the test the power output data from Hojum was used as a reference for the plant. Flow data from Hojum was then compared with the flow in the model. The result is shown in Table 4.1 below. Note that the model is subject to tweaking and tuning of input parameters and therefore it is easy to change the output of the model in either direction. In this test, parameters were tuned from raw turbine -and generator data obtained from Hojum [15], however there was no intensive tuning of the system.

$P_{Hojum}[MW]$	$Q_{Hojum}[m^3/s]$	$Q_{Model}[m^3/s]$	Error
13.818	53.84	50.3	-7 %
21.324	79,556	78.2	-1,7%
31.404	114.978	112.7	-2%
41.233	149.659	148.5	-0.7%
51.776	192.094	194.5	1.1%
55.549	204.687	211	3%
58.642	215.362	228.01	5.8%

Table 4.1. Test of output power versus flow for Hojum and the model at a head of 31 meters. [15]

To test the system dynamics towards the real plant in Hojum real operational data was obtained (see Appendix A.2). However due to technical difficulties during the gathering of the data these are deemed insufficient for a satisfying validation (see Section 5.1.1). They were however compared visually with the output of the test bench and indicated similar behaviour.

Validation against Simpov

To be able to validate the behavior of the model, a model in Simpov was made. Simpov is an electric simulation program with verified models that ÅF uses in electric system simulations. The model in Simpov consists of a generator with the same parameters as the one used in the Dymola model, connected to a constant PQ load with the same load parameters as the one in Dymola. Both the generator in the Dymola simulation and the Simpov simulation had a base production at 13.2 MW when an increase of 0.66 MW of the load was made. The result from the Simpov model was then compared with the Dymola model (see Figure 4.1.3 and Figure 4.1.4).

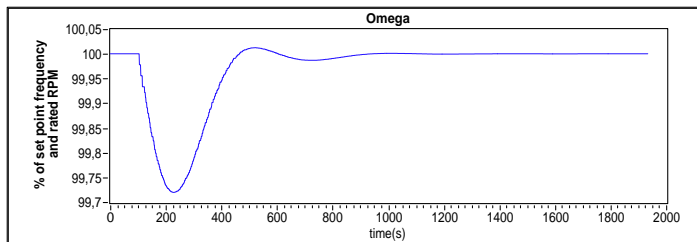


Figure 4.1.3. Frequency behavior of Dymola model. Note that X-axis is not real time but the number of samples in LabVIEW.

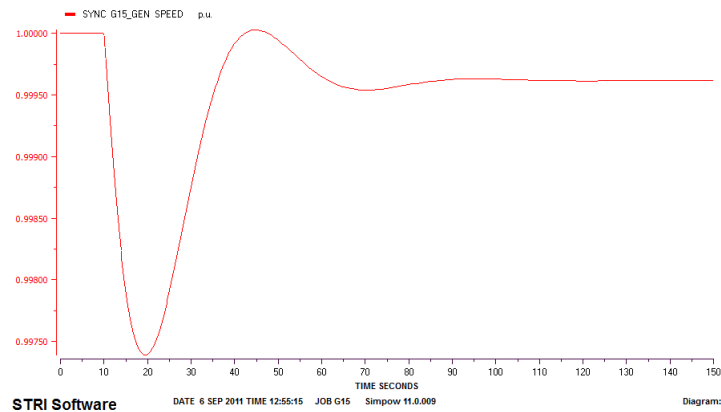


Figure 4.1.4. Frequency behavior of Simpown model.

4.2 Results

4.2.1 Interface

The interface that was built in LabVIEW had two objectives, it should give a good picture over the hydro-power plant and give information of the essential parameters of the process. The controllers for frequency, power output and water level control should be built in LabVIEW and control the Dymola model. The controllers were built in LabVIEW because it makes it possible to make changes to the controller parameters in real time while running the model. In this section a description of the interface will be made. The interface consists of two main parts, the control panel which controls the process model in Dymola and the process overview where graphs over all the essential parameter can be observed.

Control panel

The control panel in LabVIEW (see Figure 4.2.1) has a number of different parameters that influences the behavior of the model. It includes the three controllers:

1. Frequency controller seen in the upper left corner. Here the three PID parameters can be set and the frequency set point.
2. Power output controller seen in the middle left. This controller controls the desired power output from the generator when it is connected to a strong grid. Also here the three PID parameters can be set and the power output set point.
3. Water level control seen to the right of the power output control. Here the PI parameters can be set and the reservoir water level set point. Two more

parameters can be set in this control: manual overflow hatch and in flow to the reservoir which is a parameter that controls the amount of water that flows into the reservoir.

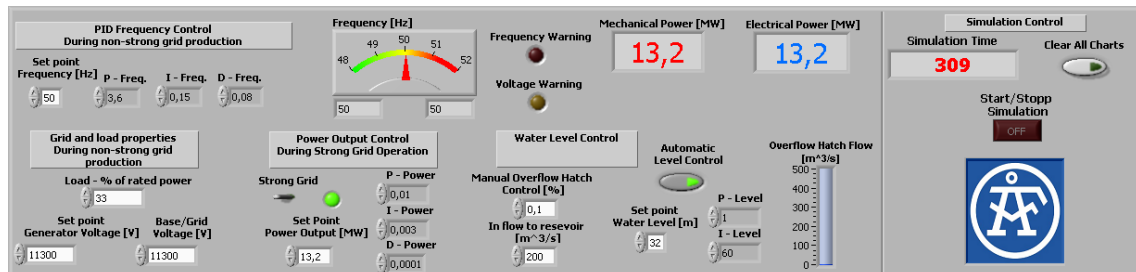


Figure 4.2.1. Control panel in LabVIEW.

Other parameters that can be set from the control panel are:

1. *Load*. This parameter sets the load used from 0-100% of the rated power of the generator. The load can change in real time, which makes it possible to do load changes while running the model to investigate the generator response.
2. *Set point generator voltage and grid voltage*. Set point generator controls the voltage output from the generator and set point grid voltage controls the overall voltage on the grid.
3. *Strong grid switch*. This switch controls the breaker between the slack node and the generator with load.
4. *Start/Stop simulation*. Starts and stops the simulation in LabVIEW.

Other values that can be seen in the control panel are:

1. *Frequency gauge*. The gauge has two markers; one that shows the desired frequency on the generator and one that shows the present frequency of the generator.
2. *Mechanical power and electrical power displays*. The mechanical power is the power given by the turbine and the electric power is the electric power output from the generator. When these two are the same the generator will run at synchronous speed.
3. *Simulation time*.
4. *Frequency and voltage warning LEDs*. These parameters can be set in the the LabVIEW model to desired value and will light up when that value is reached for the generator, to indicate if the frequency or voltage have reached a too high or low value.

Process overview

Process overview interface consist of three tabs Initialization, Overview and Detailed view (see Figure 4.2.2) explained below:

- Initialization. Different initialization parameters can be set in the Dymola model.
- Overview. Consists of a conceptional picture of the hydro-power plant (see Appendix A.1) where different process values are shown in the picture i.e. water flow through the turbine, power output etc. This is to get a visual picture of the different components of the power plant and to get a good understanding of how they influence each other.
- Detailed view. Graphs over the process parameter are showed and also a picture over a turbine with turbine parameters integrated. This tab also have four sub tabs which are sorted in the following way:
 - Omega/Mechanical Power/Flow. Omega is the frequency over the generator, Mechanical power is the power that the turbine produces and Flow is the water flow in the turbine.
 - Electric Power/Voltage/Efficiency. Electric Power is the power output from the generator, Voltage is the voltage of the generator and Efficiency is the efficiency of the turbine.
 - Turbine Head/Blade and Guide Vane Angle. Shows the current angle of the wicket gate guide vane and the runner blade angle in the Kaplan turbine.
 - Water Level. Water level of the reservoir.

The two graphs that are always shown in this tab regardless of what sub tab is shown are Control error and Control Signal to guide vane. Control error is the error from the frequency controller and Control Signal to guide vane is the control signal to the wicket gate.

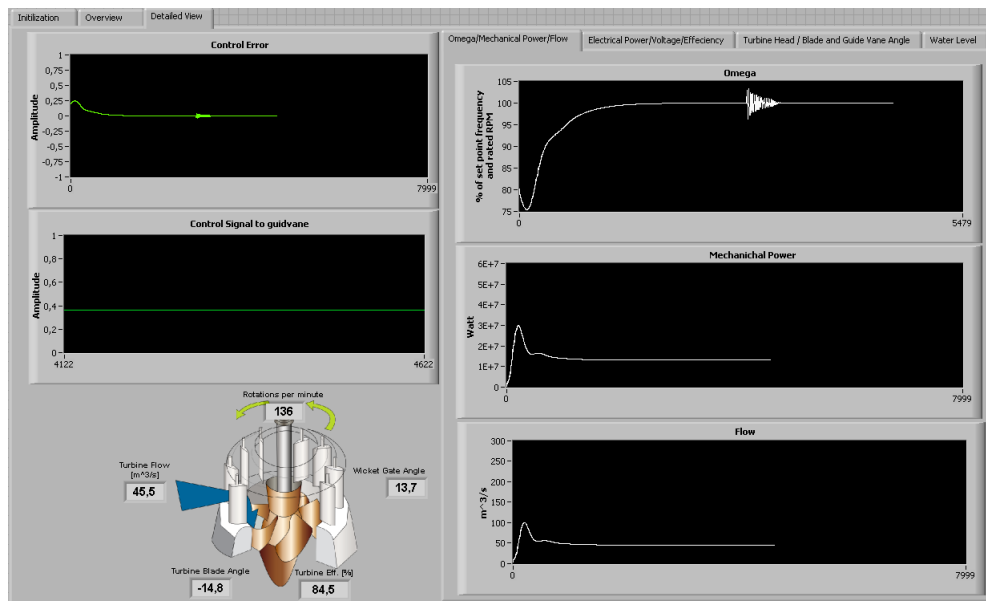


Figure 4.2.2. Process overview interface.

4.2.2 Frequency control

In Figure 4.2.3 the frequency behavior of the generator is shown after a load step. The generator has a base production of 13.2 MW before the load step. The load step is an increase in load of 0.66 MW which is one percent of the generator's rated power.

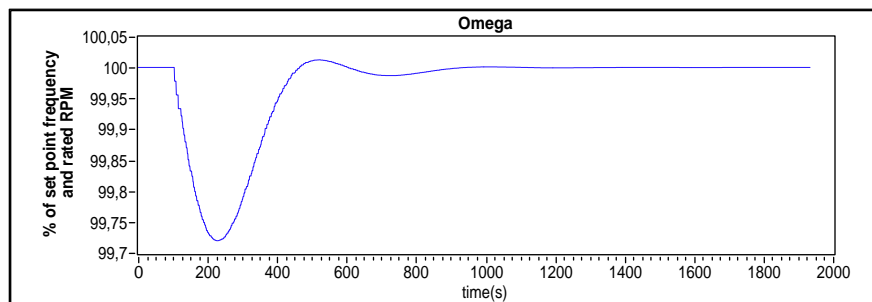


Figure 4.2.3. Generator frequency after a load increase of one percent of rated power. Note that X-axis is not real time but the number of samples in LabVIEW.

Another test that was performed was how the model would react to a loss of strong grid (see Figure 4.2.4). In this simulation the generator is running against a strong grid with a power output of 50 MW when the strong grid is disconnected. The generator goes from an output of 50 MW on a strong grid to an island grid with a small load of 0.66 MW. This will make the frequency to increase rapidly and the simulation goal is to see how the regulator handles this problem.

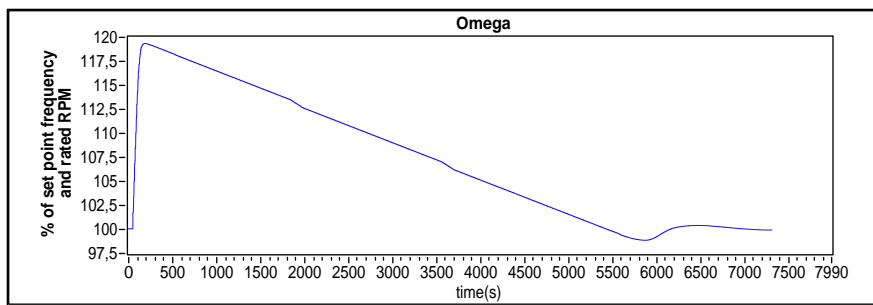


Figure 4.2.4. Frequency behavior of the generator when strong grid is disconnected at a power output of 50 MW. Note that X-axis is not real time but the number of samples in LabVIEW.

4.2.3 Voltage Control

Figure 4.2.5 shows the voltage behavior of the generator after an increase in load of 3.3 MW. The set point voltage is 11300 V.

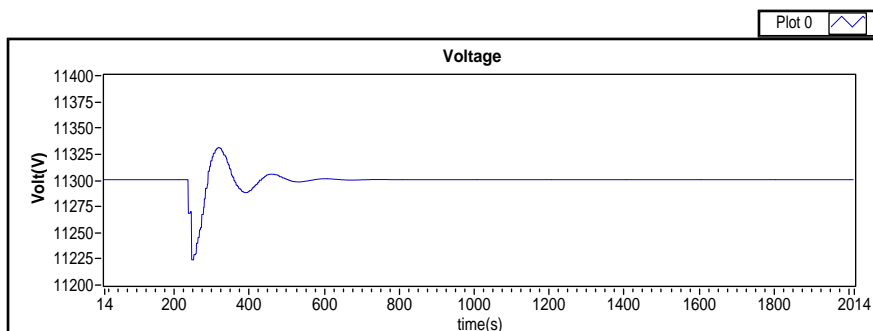


Figure 4.2.5. Voltage behavior of generator when increase in load of 3.3 MW. Note that X-axis is not real time but the number of samples in LabVIEW.

5 DISCUSSION

5.1 Results

The general results of the test bench are considered satisfactory. It has been verified functional in the sense that it can produce a clear output (data from physical model) and responds to user inputs via the GUI. The current version of the test bench has basic operational control system and operational modes which represents the functionality of a real plant in general. The test bench was intended to have a more logic based control and a detailed safety system with automatic safety procedures that takes control of the plant when something goes wrong, but due to lack of time further development could not be carried out within this project.

5.1.1 Validation

The dynamics of the test bench validates well in all aspects of operation. It behaves according to theory and give similar output to the generator models in Simpow, and the same dynamics can be seen in a similar master thesis [8]. The model was also able to handle a disconnection from strong grid were the frequency did not rise over 60 Hz (120% of set point frequency of 50 Hz) which is the industry standard. The voltage control also functions in a satisfactory way.

Main issue of concern is the validation results against the Hojum plant. The flow test (see Table 4.1) gives some indication of the performance of the test bench tuning. However it is not enough since it contains no dynamical features.

When trying to gather real time operational data there was technical difficulties with access to the PLC at Hojum. The only data gathered was plots of data with insufficient level of detail (see Appendix A.2). There is no way to compare the data with the output from the test bench other than visually, which is not enough for a satisfying validation. Hence, it is not possible to say if the test bench can be tuned to necessary level of detail to represent the Hojum plant.

5.1.2 Area of use

Due to the lack of validation against a real hydroelectric plant the test bench in its current state is not suitable for use towards any real plant operation. However, since the dynamics of the plant model are verified theoretically the system could be used as a demonstrator or educational platform.

5.2 Complications

The main complications during the project were caused by software related issues. Below follows a short description that may be taken into consideration when doing further development or similar work:

- The combination of Dymola, TOP Server and LabVIEW is not very stable due to unknown reasons. A likely cause is the DDE server used in Dymola.
- Dymola version 6.1 was used. This version has no support for the latest Mod-
elica libraries, so there is no built in support for complex math or a library for
fluid systems. The latest versions of Dymola has this, thus enabling modeling
with more detail and verified components.
- There was no good way of exporting data from graphs in LabVIEW to make
exact comparison with the simulation results from Simpow.

5.3 Future Development

Below follows what is considered to be the most interesting and plausible develop-
ment for the test bench.

5.3.1 Development the current physical model

There are many options regarding further development of the model in Dymola. Since the Dymola package is object-oriented it is natural to add components to the plant. This could include other types of turbines, surge tanks, more detailed pipe models, higher order generators and so forth. Other options are to model hardware and logic into the physical model to increase the similarities with a real plant. For example, safety valves, pressure sensors etc.

5.3.2 Connect physical model to a PLC

By connecting the Dymola model directly to a PLC a more realistic setup is cre-
ated that enables testing of real PLC code on Dymola models. This opens up the
possibility of developing, testing, writing and optimizing PLC programs off-line.

5.3.3 Deeper analysis of governor system

A more thorough investigation of a real plants governor can be investigated and implemented in LabVIEW for example. This includes procedures for emergency shutdowns, startups, testing and so forth.

6 CONCLUSION

A test bench of a hydroelectric plant has been developed to test the feasibility of the concept. The Hojum hydroelectric plant was used as a basis of design. The test bench is the result of physical modeling of the plant in Dymola and construction of an interface and governor in LabVIEW. To connect the interface with the physical model the software TOP Server acted as a socket between the two program's communication protocols OPC (LabVIEW) and DDE (Dymola).

The end product is a functional test bench of a hydroelectric plant with graphical user interface and governing system. The main features are:

- Graphical overview of the total system.
- Interchangeable design parameters of the plant, for example, length and diameter of penstock, size of reservoir, inertia in turbine and generator and lag time in wicket gate.
- Frequency and Load control during *Island Grid Operation*.
- Power output control during *Strong Grid Operation*.
- Water level control.
- Ability to tune controllers in real-time.

Plant dynamics have been validated with good results against theory, generator models in Simpow and a similar master thesis. Regarding the Hojum hydroelectric plant a complete validation of the test bench was not possible because data gathered from live operations was not to a satisfactory level of detail.

The concept of developing a test bench for demonstration and educational purposes is considered feasible. The test bench developed is capable of explaining how a hydroelectric plant function and operate. To be able to test different scenarios, new control strategies or operations concerning real plants further development is required. The current system may function as a base of development but a lot of work is required, with focus on validating the model against a real plant data, designing a more detailed control system and connecting the test bench to a real PLC system.

7 Literature and References

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A Appendix

A.1 Conceptional picture over the hydro-power plant

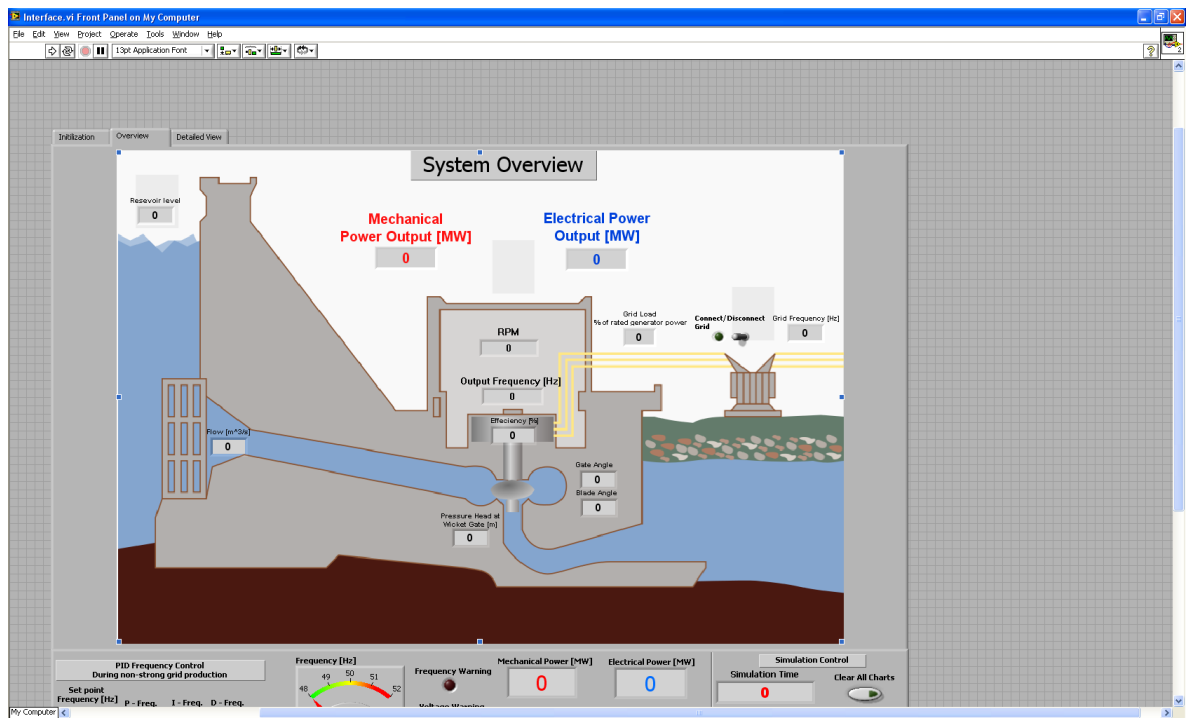


Figure A.1.1. System overview.

A.2 Gathered data from Hojum, Trollhättan

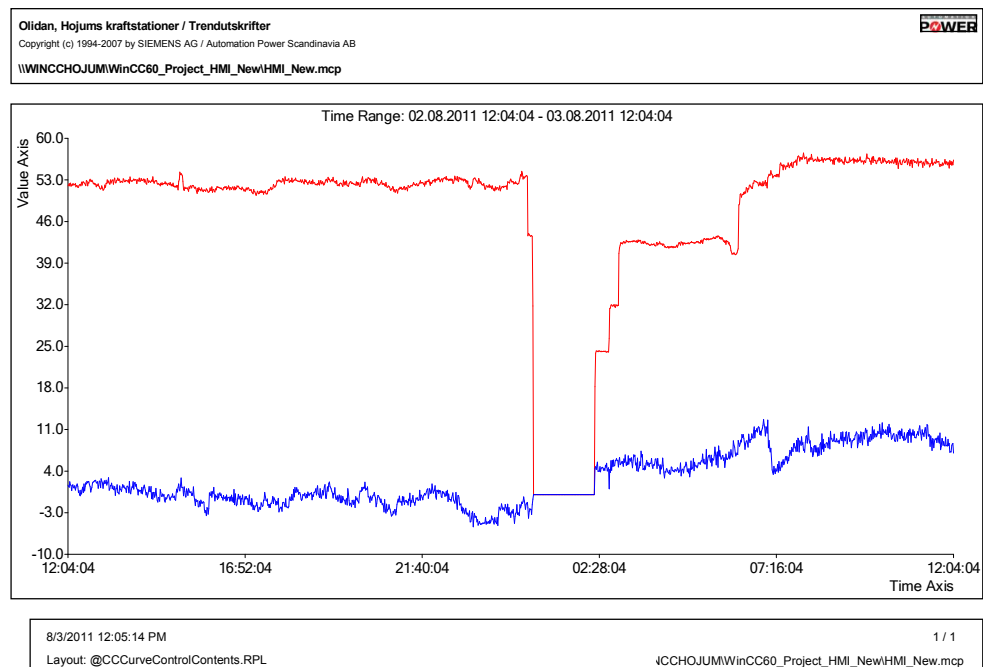


Figure A.2.1. Power output in MW(red line) blue line unknown.

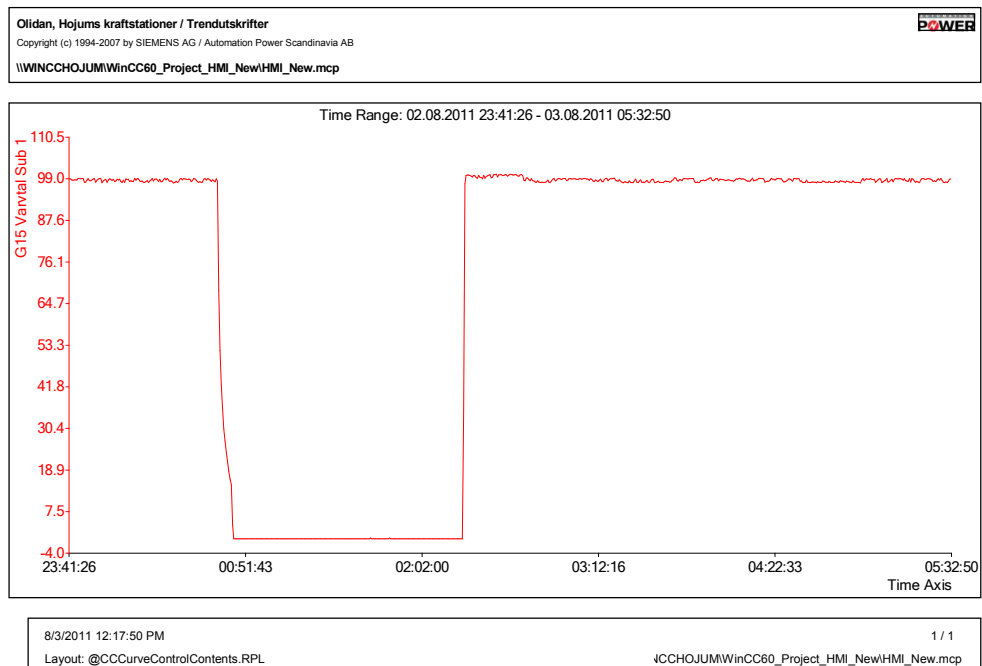
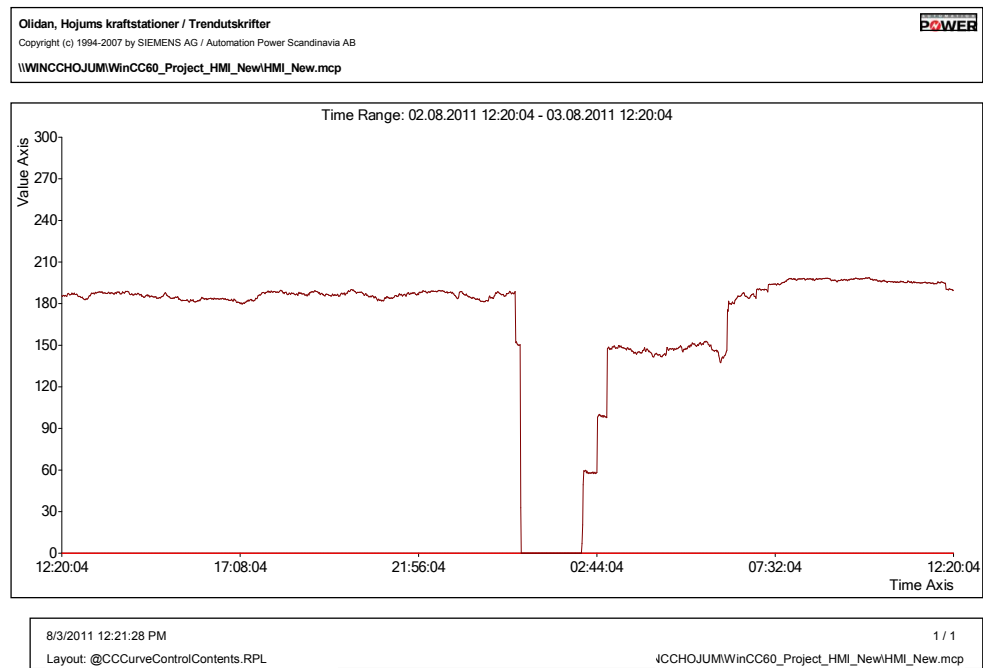


Figure A.2.2. Rotational speed in % of rated speed.

Figure A.2.3. Flow in turbine [m^3/s]

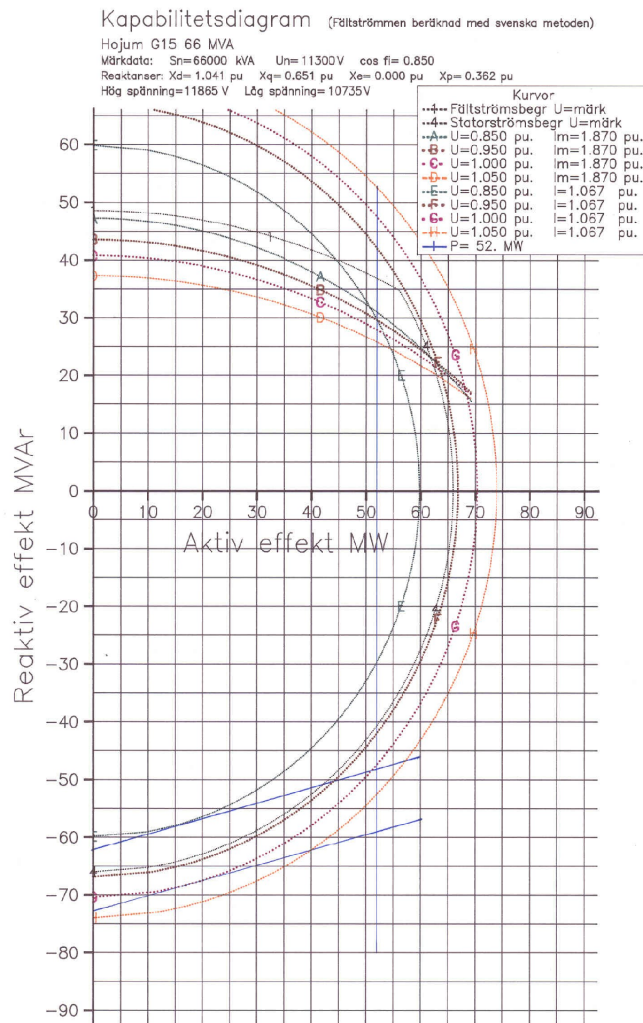


Figure A.2.4. Generator parameters from G15 Hojum