HydroPlant – a Modelica Library for Dynamic Simulation of Hydro Power Plants

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Abstract

This paper presents a library for simulation of hydro power plants. The library is designed to be an effective tool for commissioning, testing of new control strategies and verifying complete hydro plants or selected plant systems only.

Keywords: Hydro Power; Simulation; Turbine; Penstock; Reservoir

1 Introduction

The hydro plant process is on first sight easy to understand and well documented. Development of new control strategies could be accordingly based on that knowledge verified through trial and error during the commissioning. This traditional approach shows to be time consuming and expensive. Plant models available are often obsolete as they are simplified for the narrow linear range of the working area and not directly executable. Intuitive knowledge of the original developers is practically not available. Real plants are run under stringent economical demands and thus not available for testing.

The library was initially designed to test control strategies and make commissioning more efficient, and it proved to be useful for evaluation of complete plants (Figure 1).

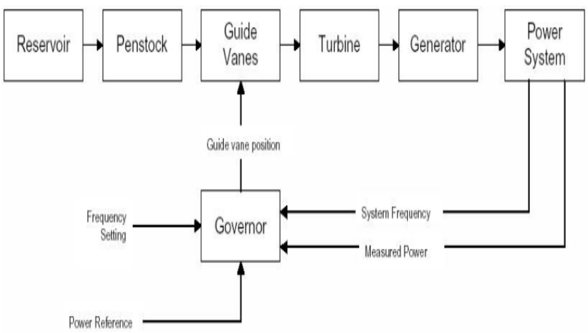

Figure 1 Component Overview

The library structure builds on four main groups of models: hydro components, electrical power system, mechanical machinery and control components. This paper covers mainly hydro components and hydro turbines exemplifying mechanical machinery. Models of the electrical power system with generator and grid address active power only and are more or less conventional but still very useful for study of the complete plant system.

2 Flow Transfer

2.1 Theory

The simulation of thermo hydraulic systems is based on three equations of mass (1), energy (2) and momentum (3) conservation in a control volume:

$$\frac{dM}{dt} = m\_dot_i - m\_dot_o = \sum m\_dot \qquad (1)$$

$$\frac{dU}{dt} = m\_dot_i h_i - m\_dot_o h_o + q + W_s - p\frac{dV}{dt} \qquad (2)$$

$$\frac{dG}{dt} = m\_dot_i v_i - m\_dot_o v_o + (A_i p_i - A_o p_o - F_f) + A\rho g(z_i - z_o) \qquad (3)$$

where; m_dot - mass flow, h - specific enthalpy, q - heat flow from (+) the environment, W_s - external mechanical energy flow, p - the media pressure in the control volume, G - the media momentum, v - media velocity, A - intake/outtake area, F_f - the friction force, z - elevation of the intake/outtake. Indices *i*, *o* symbolize entering or exiting flows to/from the control enclosure.

Conservation principles were expressed initially as partial differential equations for an infinitely small control volume (local form) and then converted into the above global formulation of differential equations of the physical enclosure modeled (Leibniz rule).

Pressure p, and temperature T, are selected as state variables of the media in a control volume, allowing calculation of all other media properties from tabulated Modelica water properties.

2.2 Basic Structure of the Flow Transfer

The basic element of the flow structure is built of two containers (control volumes) exchanging media through a single connecting module. The thermodynamic states, p and T, of control volumes are calculated from the mass and energy exchange through connecting module and from/to the environment.

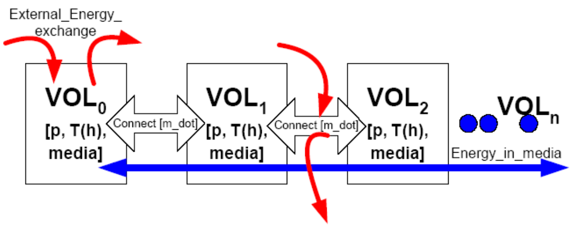

Figure 2. General concept of interconnected control volumes and connecting modules

Considering length and complexity of the plant water ways, modeling of the longitudinal pressure transfer in an elastic media was found essential.

A basic element of two volumes was accordingly expanded into a media transmission line developed initially by Heaviside as telegraph line formulation. Water conduits of the library are sliced into a number of interconnected volumes (Figure 2). Inductance and resistance are represented by water inertia and flow resistance (equation (3)), while capacitance is represented by media elasticity in the control volume.

2.3 Modeling challenges. Nonlinearities

The well established theory of the models would imply 'green light' for easy implementation in the hydro plant library. In spite of that several modeling challenges were met.

Vector of media flow velocity: Assuming control volumes part of the water conduit requires completion of the enthalpy with the kinetic energy factor $v^2/2$. Transfer of that energy to the next segment of the conduit depends on the direction of the velocity vector. The problem was addressed by inclusion of the 'flow recovery' parameter. An additional challenge of the flow velocity concerns mainly turbines, where flow vortex is an essential part of turbine design.

Nonlinearity of forces acting on the water flow: The momentum equation includes highly nonlinear force components. These are mainly momentum forces, 'm_dot*v', and friction forces, Ff, depending on the flow direction and flow velocity (Reynolds number) in laminar and turbulent regions. Library models were based on forms presented in reference [1].

Flow calculation in open channels/reservoirs: Flow in open channels was modeled from the same momentum equation as for enclosed channels, subject to the following:

- Pressure drop, the main force moving the mass, is calculated from media level difference between the adjacent volumes. Level variations depend strongly on the volume geometry.
- The main flow caused by the mass inertia is completed by additional components as e.g. water 'sliding' along the slopes of the waves.
- Friction calculation depends strongly on the channel geometry, e.g. bottom and coast lines.

3 Basic Hydro Components

The library is built on two main types of hydro components: *containers,* basic models representing control volumes in open and closed containers, and *connecting modules*, models representing media conduits.

Closed volumes represent a single container or an enclosed water segment of a long media conduit.

Open volumes represent containers with free surface between the media and the gas above allowing media compressibility to be neglected.

Generally standard Modelica connectors are used, but with *FlowPort* and *MediaPort* added. *FlowPort* connects flows of mass and enthalpy, while *MediaPort* carries vector of media property. Input and output ports of both connectors are separated.

4 Hydro Subsystems

Hydro subsystems include a reservoir, penstock and surge tank. All of those models are built of interconnected segments of control volumes and connecting modules. The number of segments is parameterized allowing automatic segment interconnection into complete subsystem. By increasing the number of segments, higher flow/pressure frequencies can be studied, but at the expense of simulation execution time.

4.1 Reservoir

The library allows simple parameterization of reservoirs fulfilling almost any desired geometry.

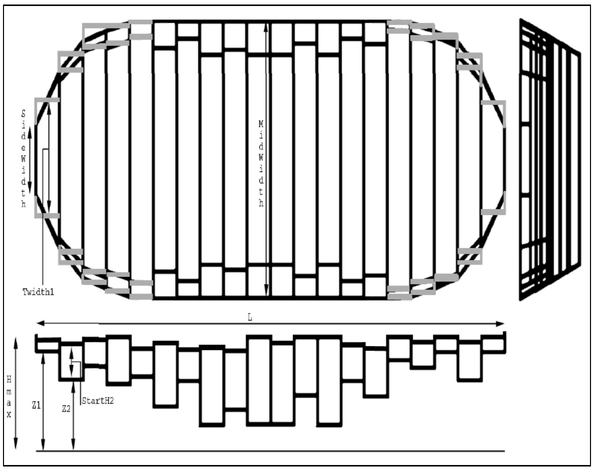

Figure 3. Parameters for dimensioning of the reservoir

Main parameters are: middle and side shore-to-shore width, height of each segment over a reference level, start water level and temperature, maximum container height and a contour factor that decides the shape of the reservoir "coast line". The contour factor k (Figure 4), represents coast line as a generalized ellipse:

$$\left(\frac{x}{a}\right)^k + \left(\frac{y}{b}\right)^k = 1 \qquad (4)$$

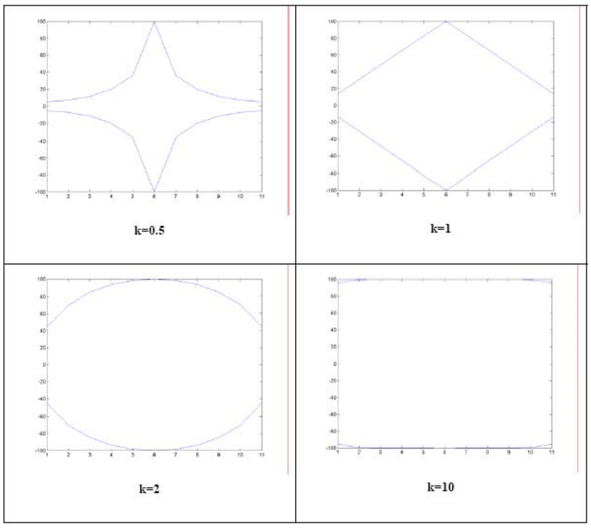

Figure 4. Some examples of reservoir coastlines depending on the contour factor *k*

Water inlets and outlets can be connected to any segment of the reservoir, allowing study of the hydro plants in cascade. Wave propagation through the reservoir caused by transients in the upstream or downstream plant can be studied. Coordination of plants can be tested to prevent the water level to exceed the maximum level allowed.

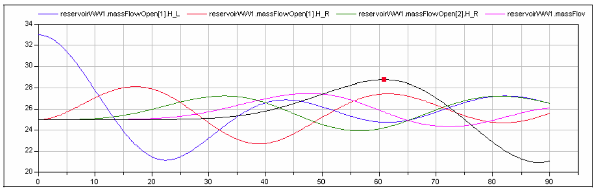

Figure 5. Wave propagation in reservoir of 5 segments and k = 1. The start level is 25m in all segments except 33m for the first one

4.2 Water ways. Penstocks and surge tanks

Water of the plant can be transported through enclosed or open conduits. The latter are basically identical to the reservoirs but of the suitable prolonged shapes. The main enclosed conduit is a penstock model. Penstocks are sliced in segments as described above and are treated by the system as flow connecting modules. Surge tank models represent vertical water columns with the upper end opened to the ambient environment.

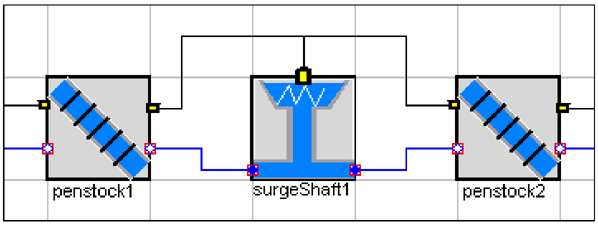

Figure 6. Example of the interconnected penstocks and surge tank

Penstocks and surge tanks can be connected directly (Figure 6), and different groups of penstocks can be coupled through interconnecting volumes. In that way almost any shape and configuration of the waterways on both the inlet and outlet side of the turbine can be modeled.

5 Electrical Power System

There are two modes of the generator modeling: unsynchronized/no-load turbine-generator and generator synchronized to the grid, in load operation. The first mode is basically non-electric, as the turbine-generator represents only a speed-controlled rotating mass. The second mode requires modeling of the active power of the grid, where the local turbine governor reads whole grid frequency and power output of the local generator. The frequency signal represents dynamics of the whole grid, or the angular speed of all rotating units of the grid.

Figure 7 introduces the main components of the power grid. *Generator and Synchronizer* represents rotating masses of the turbine-generator driven by the power from the turbine shaft, and loaded/driven by the balance of the grid production – grid load. Synchronizing part of this model generates pulses for adoption of the turbine-generator speed to the grid frequency. The *Main Circuit Breaker (MCB)* models switch between no-load to load operation allowing simulation of load rejection and connection to the grid after a synchronization phase handled by the *synchronizer*.

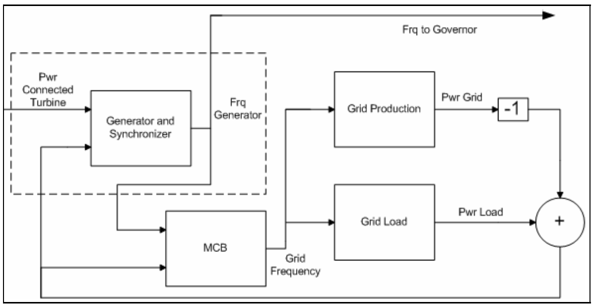

Figure 7. Overview of the power grid

The load model, *Grid Load*, represents the active power demand of the grid. The load of the grid is divided into three groups: resistive, frequency dependent and quadratic frequency dependent. The number of units within each group is decided through parameterization. The response to step changes of the load is simulated by using first order transfer functions.

As the grid load is constantly changing a normal distributed random number generator was added to the load of each group. In addition to this there is also the option to add a disturbance at any given time.

The *Grid Production* model is the representation of all other production units connected to the grid. The grid production units are divided into different groups depending on their response time. This enables simulation of different behavior depending on the types of power plants connected to the grid.

6 Mechanical machinery

Models of mechanical machinery cover main types of water turbines, Pelton, Francis and Kaplan. Turbine models are complete with guide vanes and runner angle actuators.

6.1 Actuators and servo motors

The actuators are modeled as first order transfer functions with a time constant representing the actuator response time. Transfer functions are complemented by multiple speed limits to allow simulation of multi-step opening and closing of the guide vanes and runner angles. Adding play and hysteresis allows analysis of the influence of obsolete equipment. The model of the Kaplan servo motors includes a Kaplan Cam curve adjusted for the actual head of the water.

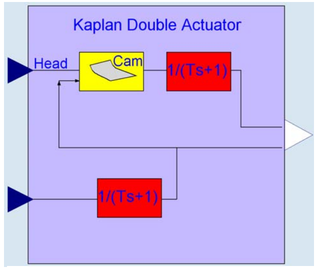

Figure 9: Kaplan servo

6.2 Models of water turbines

The simple approach to models of water turbines builds on the assumption that flow through the turbine can be estimated the same as for orifices, i.e. $Q_T = C_v \text{ sqrt}(\Delta p_T)$, where C_v is the guide vane opening factor. Power on the turbine shaft would be accordingly $P_T = Q_T \Delta p_T \eta$, where η is the total turbine efficiency. The pressure drop over the turbine, Δp_T, is available from the models of water ways. This simple approach could be satisfactory but only if there is tabulated data of C_v and η available. Both factors are functions of runner speed, water head, runner angle, etc. The problem will complicate further in case modeling interest is bound to phenomena of unusual runner situations, as at the turbine start-up, shutdown or load rejection. In reality such detailed information is not available or it would take a considerably long time and cost to get it.

HydroPlant library provides models according to this simple approach above or alternatively as detailed

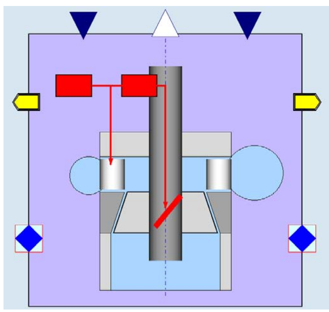

Figure 8. Icon of detailed Kaplan model

models calculating water velocity vectors on the inlet and outlet of the turbine runner.

The detailed model (shown schematically as Modelica icon in Figure 9) covers three essential volumes of the turbine; scroll case, guide vane and runner (GVR) volume and draft tube. Flows are calculated separately for guide vanes, for runner and for leakage through runner circumference from GVR-volume to draft tube.

Vectors of water flow velocities are shown in Figure 10 (from ref [3]); u is the velocity of the runner (1: inlet, 2: outlet), v is the velocity of the water flow in relation to the runner, c is the external velocity of the water entering (1) and leaving (2) the runner.

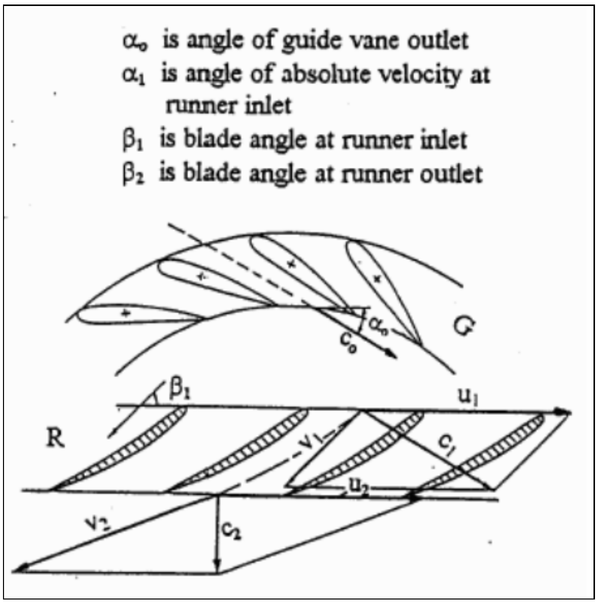

Figure 10: Angles of Kaplan water flow velocities

Power on the turbine shaft is now calculated from the change of the momentum on the runner:

$$P_T = m\_dot \cdot \omega \cdot (r_1 \cdot c_{u1} - r_2 \cdot c_{u2}) \qquad (5)$$

Vectors c_u = c cos(α), for α angle between c and u vectors. One will ask naturally if information on all angles required here is easier to get than for factors C_v and η? This information is calculated automatically by assuming the runner and guide vanes are well designed; it means mainly the following:

- Maximum efficiency is assumed at the nominal power at the nominal head and speed
- Vector v_1 is assumed at the nominal conditions to coincide with angle β_1.
- Vector c_2 at the nominal conditions enters draft tube at $\alpha_2 = 90^o$

7 Control Challenges

The implemented controller is a standard PID turbine governor, complete with a feed forward for power change control. The error signal to the PI is:

$$e = \quad \Delta f + ep \cdot \Delta P \qquad (5)$$

where Δf is the frequency error, ΔP is the power error and ep is the speed regulation factor.

Setting of PID parameters depends on various control challenges.

Water level control: Each hydro power plant has an assigned maximum water level allowed in the reservoir for environmental reasons. If this level is exceeded the hydro plant is normally fined. Since the amount of water stored corresponds to stored energy, the power plants will try to be as close to this level as possible. Problems arise when the water reservoir level is close to the max allowed level and the power demand is low. In situations like this the plant will be forced to let a certain amount of water through the gates which is a waste of money for the plant and produces environmental costs of dumping large amount of water down the river. Tuning this kind of control system takes a long time due to the long time factor of a large reservoir which often results in settings of the controller for the worst case scenario. Using models to tune this kind of system would both save time and improve the performance of the controller.

Scheduling of turbine governor settings: Conventional turbine governors have normally two sets of PID parameters; one for no-load mode of operation and one for the generator synchronized to the grid. Digital governors allow a practically unlimited number of PID settings, but logic switching between those settings will become complex, error prone and difficult to verify. HydroPlant library was developed initially for testing different methods of adapting PID settings to the actual mode of operation, actual water way configuration and to the actual system load and dynamics. An adaptive approach requires on-line identification of the dynamics of both the power grid and the local plant.

Nonlinear plant behavior: Plants having complex waterways can be difficult to control. It will change dynamics depending on the power generated (nonlinearities). HydroPlant library will allow development of the simplified real-time models of the plants allowing continuous tuning of the PID settings.

Varying power grid: When tuning PID parameters or developing alternative control schemes, it is of importance to know the dynamics of both the power grid and the local plant simulated. Identification of the grid is more complicated as the main grid information is provided in frequency signal only. Identification considers mainly grid size in relation to the size of the local generator. If that relation is large, the power plant will not affect the grid frequency noticeably (stiff grid) and the PID settings can be chosen more aggressively. But in the other case (soft grid), precautions need to be taken. In this case overshoots and oscillations in the local plant will affect the grid frequency and the PID settings should consider mainly grid stability. The problem gets more complicated as the grid changes, and the local generator works both on the stiff and soft grid. The HydroPlant library facilitates development of techniques for continuous, on-line, grid identification.

Schemes of joint control of plant units: The majority of plants run several turbine-generator units on the common water ways. There are serious control problems to be solved here to allow most efficient plant operation or to avoid certain power divisions causing vibrations, pressure oscillations or other forbidden working situations.

8 Simulation Results

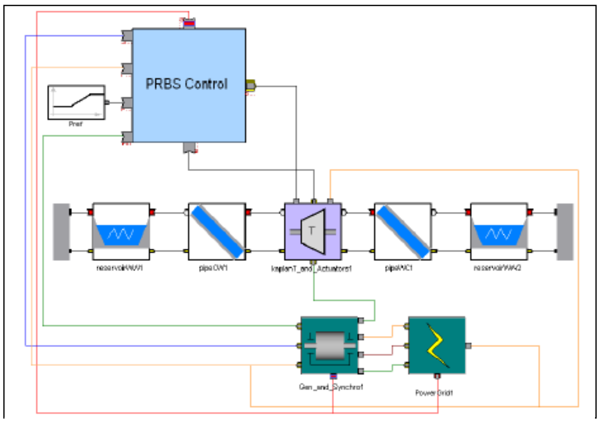

Figure 11. Model of a complete hydro power plant

Simulation results from the example of a simple hydro power plant (Figure 11) are briefly presented here. For a more in-depth result analysis please refer to [4], and to the HydroPlant manual [5].

8.1 No-load, synchronizing and loading

This example will illustrate a hydro power plant acting under no load and when connected to the power grid. Simulation starts when the grid load is increasing and the grid frequency is falling below the nominal level (Figure 12).

The turbine starts and the governor (in no-load mode of operation) controls turbine speed to the generator's nominal frequency as it can be seen during the first 110s of simulation.

After 110s synchronization is initialized, by sending pulses to frequency set point in order to match the generator frequency to frequency of the power grid.

After 300s the frequency of the generator is synchronized to the grid frequency, the MCB is closed, the power reference is set to 50MW and new set of PID parameters is applied. Generator power output increases until new load balance is reached.

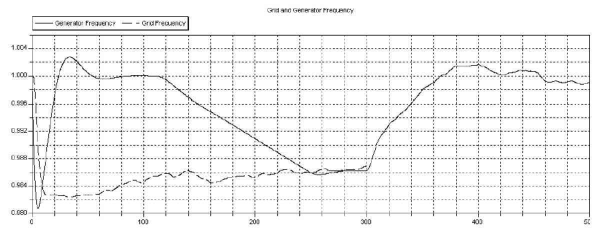

Figure 12. Frequency of the grid and local generator during start and synchronization

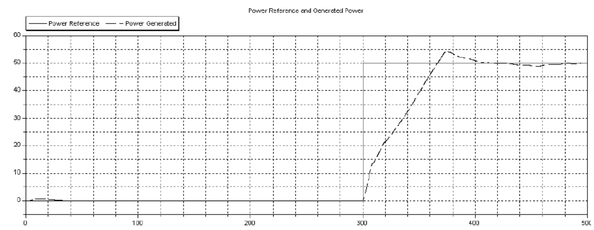

Figure 13: Loading of the local generator

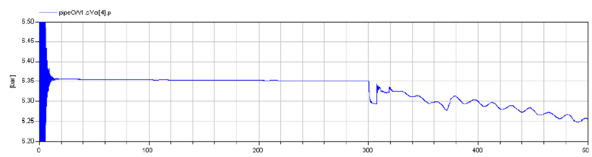

Figure 14: Pressure drops at the turbine runner due to the water acceleration in the penstock.

8.2 Load Rejection

The particular shape of the turbine velocity profile during load rejection is normally a guaranteed issue and the ultimate test of turbine governor quality and its settings.

Figure 15 presents opening of the MCB in 500s of simulation. The speed rises but after approximately 100 sec is controlled back to normal. Behavior of the guide vane and Kaplan angle servos can be studied on Figure 16. As the guide vane servo is faster then angle servo, a large combination error can be seen. The combination error means a discrepancy exists between optimum angles leading water through the turbine, which affects the turbine efficiency drastically.

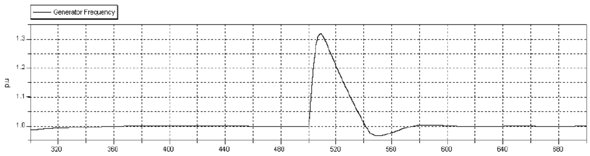

Figure 15: Generator frequency at the load rejection

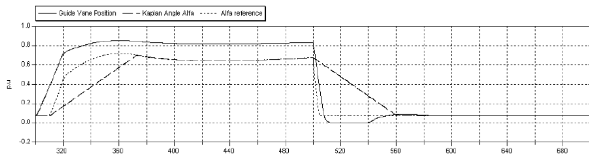

Figure 16: Guide vane position, Kaplan angle and angle reference

References

[1] Elmqvist, H, Tummescheit, H and Otter, M (2003): "Object-Oriented Modeling of Thermo-Fluid Systems". Dynasim Sweden, UTRC, USA and DLR, Germany.

[2] Roberson, Cassidy, Chaudhry (1998): "Hydraulic Engineering. Second edition" John Wiley & Sons, New York, USA.

[3] Kjølle, A.: Hydropower in Norway. Mechanical Equipment. A survey

[4] Slättorp, K, Tuszynski, K (2005): "Model of a Hydro Power Plant – New Algorithm for Turbine Governors", Master Thesis. Dept. of Automatic Control, Lund Inst, of Technology, Lund, Sweden

[5] HydroPlant Library. The Manual
(may be distributed on request)