THE TRAINING SIMULATOR FOR THE GHAZI-BAROTHA HYDRO-POWERPLANT

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Abstract

The paper presents the modelling of the 1450 MW hydro-powerplant (HPP) Ghazi-Barotha, Pakistan. The purpose of the modelling is to design and built the training simulator for the operator personnel. The paper focuses on the hydrodynamic model of the plant. The most complex subsystem is the power channel. It was initially modelled by a system of partial differential equations that can be solved by the method of characteristics in order to obtain discretised (in length and time) model of the channel. After the simplification, the model was realised as a combination of the admittance model and the hybrid model that is very well suited for the simulation purpose. Four types of gates are used in the system and each type is modelled in the paper. The hydrodynamic model is completed by describing the barrage and the forebay ponds. The electrical part of the model includes the model of five turbines and corresponding units and the model of the high-voltage switchyard. Electrical models are much faster and are therefore drastically simplified. The main problem is huge amount of signals that have to be calculated in real time. Most components are modelled as simple automata. There are also some continuous-time subsystems that were discretised and simulated as discrete transfer functions.

Keywords: training simulator, hydrodynamic model, electrical model

Presenting Author's biography

Sašo Blažič received the B.Sc., M. Sc., and Ph. D. degrees in 1996, 1999, and 2002, respectively, from the Faculty of Electrical Engineering, University of Ljubljana. Currently, he is Assistant Professor at the same faculty. His main interests include adaptive, predictive and fuzzy control with a stress on the robustness issues of adaptive control.

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1 Introduction

This paper presents the design of the simulator for the hydro-powerplant (HPP) Ghazi-Barotha. The latter is located in Pakistan in the upper flow of the Indus river, approximately 100 km to the south of Islamabad. The HPP consists of the barrage, the power channel (its length is 51.9 km, nominal flux is 1600 m^3/s, and the water depth is 9 m), and the power complex. The main parts of the latter are 5 generators (cumulative power is 1450 MW) and a 500 kV high-voltage switchyard (6 bays connecting 6 power lines).

From the figures above it can be seen that the HPP is a huge object. An extensive control and supervisory system has been built that is used for changing modes of operation, starting up and shutting down the HPP and many others operations. In spite of that, the human operators are present all the time and can react in the case of difficulties. It is also possible to run the HPP in manual mode. For these reasons, the operators have to be very familiar with the plant and the consequences of all their actions. To achieve this level of knowledge, all operators have to undergo a special training to be capable of solving different problems they may encounter. The HPP is neither suitable nor acceptable for the training, and therefore one of the demands of the contractor was that a special training simulator has to be built.

Before building the simulator, a deterministic model of the plant has to be available. The most important information when building the model is always its purpose. The most interesting subsystem from the theoretical point of view is the power channel. Open channels hydraulic models are very well known in the scientific community. Very good models for prismatic channels have existed for several decades. Lately, those models were improved [3] [6] by including new elements. Very often, the channels were modelled for the control purposes [1] since good control is very important for saving the water when designing the irrigation systems.

Since our model is used for training purposes, it does not have to be very precise but it has to show similar qualitative behaviour as a real plant. For that reason, unimportant components of the system are not modelled. This is quite important if we have in mind that tens thousands of binary signals and several thousands of analogous signals are actually measured on the plant.

The whole model of the HPP was realised as a discrete time system and implemented in the executable designed in C++ and run in the Windows environment. The computer implementation of the simulator brought up several programming and communication issues not analysed in this paper.

Section 2 discusses the simplifications introduced into the model, section 3 describes modelling of the hydrodynamic system, section 4 briefly deals with "electrical model" and section 5 concludes the paper.

2 Simplification of the HPP model

When one wants to build the simulator, he needs a model. The quality of the model is defined by its intended use. Since our model is used for training purposes, it does not have to be very precise but it has to show similar qualitative behaviour as a real plant. For that reason, unimportant components of the system are not modelled. The following simplifications were introduced into the model/simulator:

- The model was simplified and several presumptions were made to achieve speed and real-time property of the training simulation system.
- Simplification and neglecting of unimportant properties of the plant subprocesses leads to a deviation of results between the simulation and the real plant behaviour. These deviations cannot be suppressed due to a number of unknown system parameters, but should be small enough to provide training and basic feeling of the plant to the operator.
- "Electrical" part of the plant was modelled as a static system since its dynamics are very fast compared to the dynamics of the "hydrodynamic" part. Slight exception of this rule is the simulation of the starting procedure of the turbine that was modelled as an automaton, i.e. the next phase in the procedure starts after the completion of the previous one. The whole model of the HPP was realised as a discrete time system.
- Control algorithms were modelled as a part of the simulator. These control algorithms were limited to the "low level" control functions (excluding medium and high level control functions from simulation). In this particular case, only control in remote manual mode was enabled. That means that the operator cannot control variables used in automatic mode since this medium and high-level control functions are not simulated. On the other hand, the automatic functions are not so interesting for the training since the actions from the operator are very limited in that mode.

In the beginning two things have to be done:

- The system has to be subdivided into smaller components with known dependencies.
- It has to be chosen how the system will be modelled. Due to the nature of the signals in the HPP, two different approaches have been taken. Some subsystems were modelled as continuous linear time-invariant systems that are simulated as discrete transfer functions with

appropriate sampling time. Some systems are clearly event-based, and were modelled as automata. For the first systems, time synchronisation was done between each calculation of the model, while the latter subsystems were called asynchronously.

It is obvious that such big system has to be subdivided into smaller components that are easier to model. In our case the following division has been made:

- Hydraulic model, realised by the following 7 subsystems:
  - Barrage pond (BP),
  - Standard Gates (SG) – 20 of them,
  - Undersluice Gates (UG) – 8 of them,
  - Head Regulator (HR) – 8 of them,
  - Power Channel (PCh),
  - Tail Regulator (TR) – 4 of them,
  - Forebay and Spillway (FB&SW).
- Electric model, realised by 2 subsystems:
  - Generators (GEN) – 5 of them,
  - 420kV Switchyard (HV) – consisted of 6 bays.

The hydraulic and the electric part can be modelled completely independently; they also have only one common part – the flux over turbines.

3 Hydrodynamic model of the HPP

The schematic representation of the complete hydrodynamic model of the HPP is shown in Figure 1. It consists of the channel model with head and tail regulator gates, the barrage pond with standard and undersluice gates, and the forebay. The interconnections between the subsystems of the hydrodynamic part are shown in Figure 1. Each of the subsystems can be modelled independently. Obviously, the different gates can be modelled similarly, but the problem was that not enough data were available. To circumvent this problem, the mixed approach to modelling was done – one part was modelled by theoretical approaches and then some parameters were estimated by the data available.

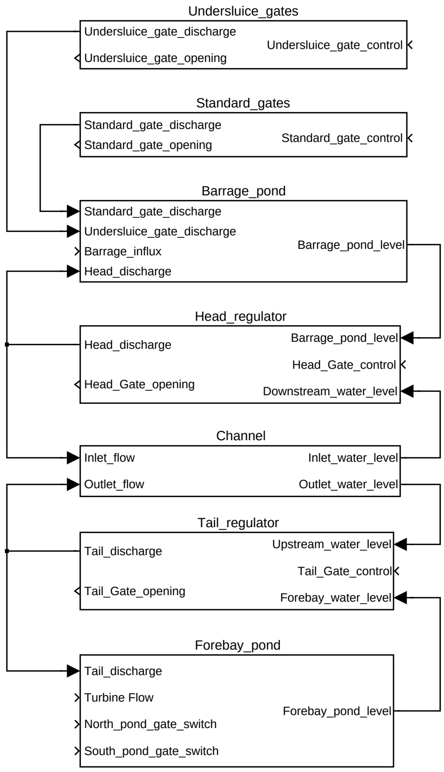

Figure 1 Interconnections of the subsystems in the hydraulic part of the HPP

3.1 The channel model

The most interesting subsystem from the theoretical point of view is the power channel. The channel is modelled as an open prismatic channel. The momentum and continuity equations for open channels are [5]

$$g\frac{\partial y}{\partial x} + gS - g\sin\alpha + V\frac{\partial V}{\partial x} + \frac{\partial V}{\partial t} + \frac{V}{A}q = 0 \quad (1)$$

$$VT\frac{\partial y}{\partial x} + T\frac{\partial y}{\partial t} + A\frac{\partial V}{\partial x} - q = 0 \quad (2)$$

where y is the depth of the water, g the gravity constant, α the slope of the channel, V the velocity of the water, T the top width of the prismatic section, A the cross-section of the channel and q the lateral in/out flow, which can be in our case set to 0. The slope of the energy grade according to Manning is

$$S = \frac{n^2}{{C_m}^2}\frac{V^2}{R^{4/3}} \quad (3)$$

where $C_m = 1$, n is the Manning roughness factor and $R = A/P$ the hydraulic radius with P the wetted perimeter.

Equations (1) and (2) are partial differential equations which can be solved by the method of characteristics. With this method the channel is discretised in length and time as shown in Figure 2.

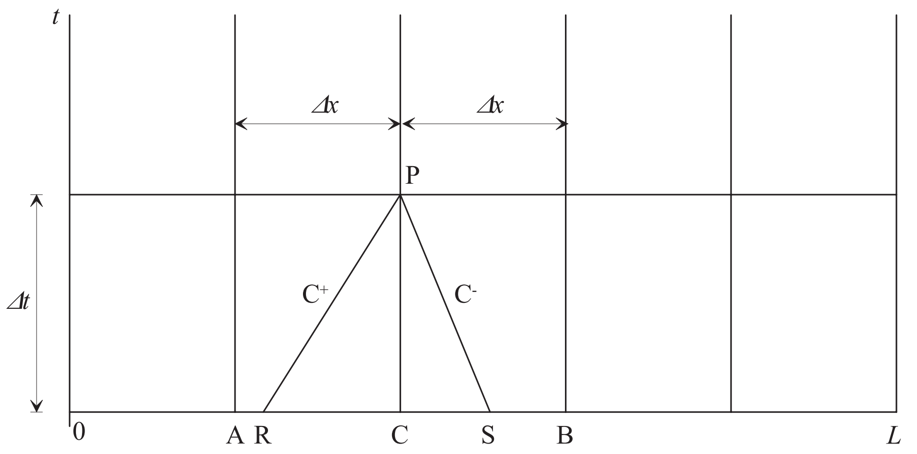

Figure 2. Discretisation of the channel

Equations (1) and (2) can be rewritten along characteristics (C^+ and C^-) as

$$V_P - V_R + \frac{g}{c_R}(y_P - y_R) + g(S_R - S_O)\Delta t + \frac{q(V_R - c_R)}{A_R}\Delta t = 0 \quad (4)$$

$$X_P - X_R = (V_R + c_R)\Delta t \quad (5)$$

$$V_P - V_S - \frac{g}{c_s}(y_P - y_S) + g(S_S - S_O)\Delta t + \frac{q(V_S + c_S)}{A_S}\Delta t = 0 \quad (6)$$

$$X_P - X_S = (V_S - c_S)\Delta t \quad (7)$$

In equations (4)-(7) the indexes denote the points along the channel (see Figure 2). The characteristics have the slope $V \pm c$ where

$$c = \sqrt{\frac{gA}{T}} \quad (8)$$

is the velocity of the surface wave propagation. The initial conditions of equations (1) and (2) determine the values of velocity V and depth y inside the channel at time $t = 0$. The boundary conditions determine one of the quantities (V or y) of both ends of the channel for all times. The other quantity is determined by equations (4) and (6) for each end of the channel, respectively.

So for $t = 0$ velocity V and water level y are known along the channel, and velocity and depth can be evaluated at point P at the time Δt according to

$$y_P = \frac{1}{c_R + c_S}\left\{ y_S c_R + y_R c_S + c_R c_S \left[\frac{V_R - V_S}{g} - \Delta t(S_R - S_S) - \frac{q\Delta t}{g}\left(\frac{V_R - c_R}{A_R} - \frac{V_S + c_S}{A_S} \right) \right] \right\} \quad (9)$$

and

$$V_P = V_R - g\frac{y_P - y_R}{c_R} - g\Delta t(S_R - S_0) - \frac{q\Delta t}{A_R}(V_R - c_R) \quad (10)$$

respectively. The velocity of the water, velocity of the surface wave propagation and the water depth at point S can be obtained by linear interpolation yielding

$$V_S = \frac{V_C - \Theta(V_C c_B - c_C V_B)}{1 - \Theta(V_C - V_B - c_C + c_B)} \quad (11)$$

$$c_S = \frac{c_C + V_S\Theta(c_C - c_B)}{1 + \Theta(c_C - c_B)} \quad (12)$$

$$y_S = y_C + \Theta(V_S - c_S)(y_C - y_B) \quad (13)$$

where $\Theta = \Delta t / \Delta x$.

Similarly for the point R:

$$V_R = \frac{V_C + \Theta(-V_C c_A + c_C V_A)}{1 + \Theta(V_C - V_A + c_C - c_A)} \quad (14)$$

$$c_R = \frac{c_C - V_R\Theta(c_C - c_A)}{1 + \Theta(c_C - c_A)} \quad (15)$$

$$y_R = y_c - \Theta(V_R + c_R)(y_C - y_A) \quad (16)$$

The channel data are obtained from [2] and the Manning roughness factor was determined taking into account that the depth of the water is kept constant (at 9 m) at the channel-flow of 1600 m^3/s. The slope of the channel is 5.9 m/52 km.

The only way to verify the obtained model was to calculate the steady state values in the model at different water flows. Steady state values were obtained in two ways:

- By setting the time derivatives in equations (1) and (2) to zero and simulate ordinary differential equations with respect to x yielding profiles of the water level and velocity, respectively, for various flows (400 m^3/s to 1600 m^3/s) as shown in Figure 3a.
- By simulation of the complete partial differential equations for sufficiently long time.

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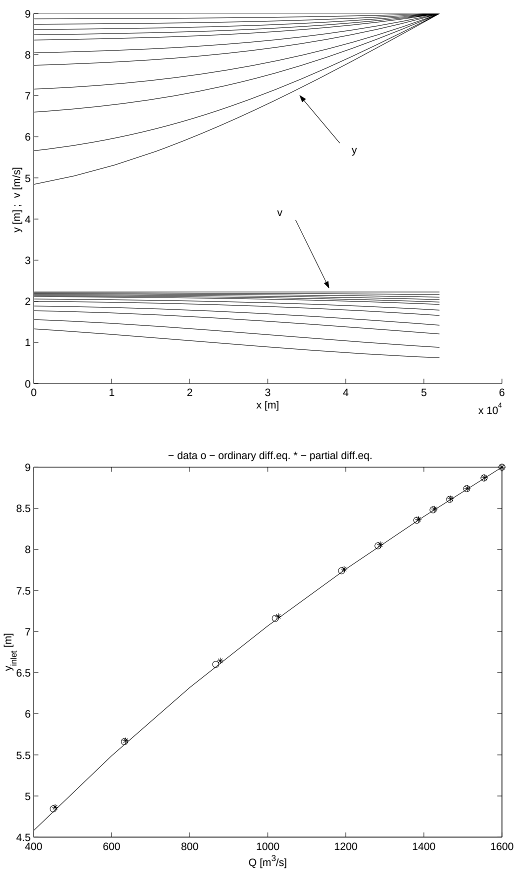

Figure 3. a) Profiles of the water level and velocity; b) The level of inlet water with respect to flow

Both methods result in almost the same level-flow static curve (for water level and flow at the inlet of the channel) if the level of the water at the outlet was fixed at 9 m. Both theoretically obtained static curves are shown in Figure 3b together with the curve given by the channel data [2]. Excellent coincidence can be seen what verifies the proposed model for the use in the simulator.

However, the solution using the method of characteristics is quite time-demanding. For the use in the simulator, a simplified model is proposed. It can be obtained by identification of the model obtained by the method of characteristics. It is a combination of the lumped parameters hybrid and the admittance models for the inlet and outlet part of the model, respectively. Also the flows Q rather than velocities were used as inputs to the model since flows are actually measured in the channel. The inlet part of the model is described by

$$y_i = G_{ii}Q_i + G_{oi}Q_o \tag{17}$$

and the outlet part by

$$y_o = G_{io}Q_i + G_{oo}Q_o \tag{18}$$

where indexes i and o denote the inlet and the outlet of the channel, respectively.

The four transfer functions obtained by means of identification are:

$$G_{ii} = \frac{8.409s + 0.002875}{2.16 \cdot 10^6 s^2 + 7500s + 1} \tag{19}$$

$$G_{io} = \frac{1}{270000s + 1} e^{-4500s} \tag{20}$$

$$G_{oi} = \frac{0.07}{7200s + 1} \cdot e^{-7200s} \tag{21}$$

$$G_{oo} = -\frac{5101s + 2.664 \cdot 10^{-5}}{8 \cdot 10^7 s^2 + 270300s + 1} \tag{22}$$

The obtained model has flows as inputs and water levels as outputs. The linear model is not adequate to model the system in different operating conditions. To overcome this problem, a non-linear static block has been added in each branch to obtain a Hammerstein type model. The corresponding nonlinearities were also obtained by the nonlinear distributed parameter model. Admittance model is not suitable for simulation since it is integrating in nature and operating point is poorly defined. To overcome this, the inlet water level is calculated from inlet flow and outlet water-level (and not outlet flow as equation (17) implies). The complete scheme of the model is depicted in Figure 4.

The simplified (lumped parameter) model was verified as follows: Both, simple and distributed parameters models were driven in parallel with forced inlet flow, changing as shown in Figure 5a. The outlet flows of both models were forced by I – type controllers with the same parameters. Figure 5b, c, and d depict the outlet flow, the inlet water-level, and the outlet water-level, respectively.

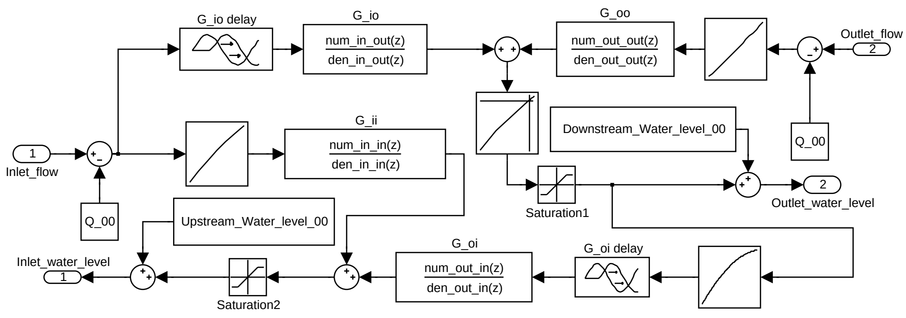

Figure 4. The complete model of the channel

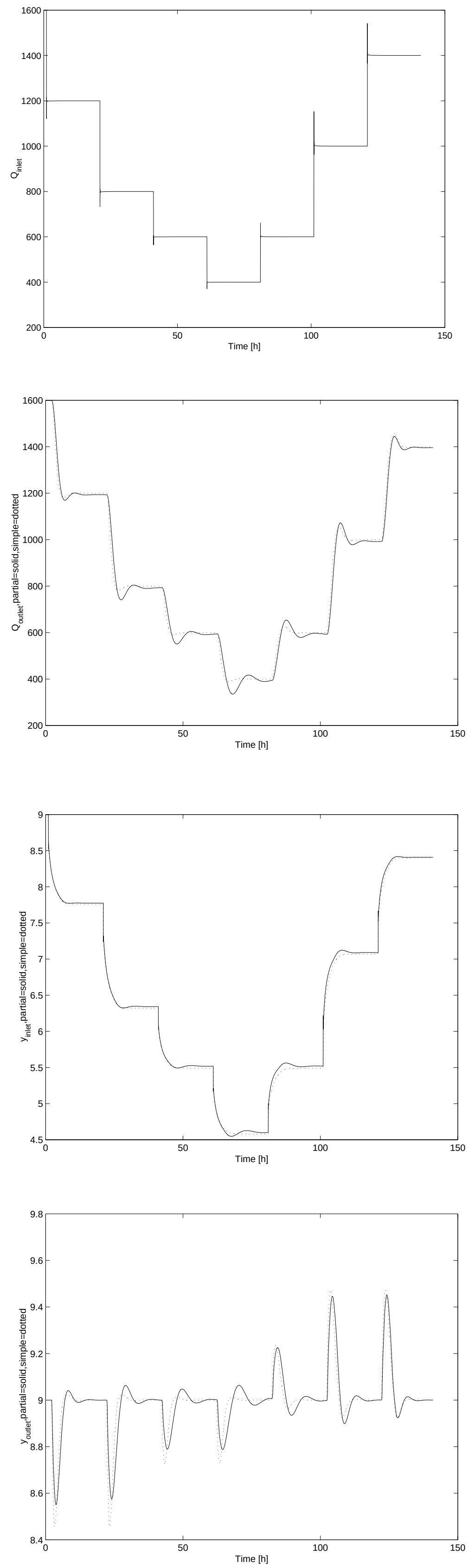

Figure 5. Verification of the channel model: a) The forced input flow for verification, b) The verified outlet flow, c) The verified inlet water-level, d) The verified outlet water-level

3.2 Modelling of gates

As already mentioned, they are four types of gates used in the system. Models are similar, but have some specific characteristics. In general the model of a gate can be represented by a static function with three inputs (upstream water-level, downstream water-level and gate opening) and gate flow as an output. The gates can operate in submerged flow and free-orifice flow what also affects their characteristics. Theoretically, all these gates can be modelled [4]. But there are some parameters that were not available. Our choice was to adapt the equations slightly and also add some nonlinear static blocks to fit the model to the plant at different operating conditions.

The standard gates are much simpler. Since these gates only influence the amount of water that enters the bed of the river Indus and consequently the level in barrage pond, this model is not so important and can be simplified. The gate discharge depends upon the positions of the gate solely and the dependence can be realised by a 1-D look-up table. The same holds for the undersluice gates.

However, the head regulator gate cannot be simplified to that extension. The gate discharge depends upon the head gate position, barrage pond level and channel upstream water level. In [2] only the steady state discharge flows are given . The steady state head regulator flow Q_{ss} depends only upon the head gate position h_{gate} and barrage pond level $h_{barrage}$. The flow data in [2] were therefore realised as a two dimensional look-up table:

$$Q_{ss} = f(h_{gate}, h_{barrage}) \qquad (23)$$

The steady state water level downstream the head regulator gate (the water level at the channel inlet $h_{ss,inlet}$) is a function of the channel flow and is given in [2]. Taking into account the difference between the steady state (at the given Q_{ss}) and the actual water level at the channel inlet, the additional flow can be calculated:

$$Q_{additional} = K\,\mathrm{sign}(h_{inlet} - h_{ss,inlet})\,h_{gate}\sqrt{|h_{inlet} - h_{ss,inlet}|} \qquad (24)$$

where h_{inlet} is the actual water level at the channel inlet and K a constant which was estimated from the data in [2]. The flow through the head regulator gate can be obtained summing contributions in equations (23) and (24).

The tail regulator gate discharge depends upon the tail gate position, forebay pond water level and channel outlet water level. In [2] the discharge characteristics are given for the channel outlet water level of 333.75 m. The complete tail gate discharge model was obtained supposing that in the submerged orifice flow the characteristics remain the same if gate upstream and downstream water levels difference remains the same. The free orifice flow, however occurs earlier and limits the tail discharge.

3.3 Pond water levels

There is a huge barrage pond that provides water for the channel and is situated directly above the power channel. Its model is quite simple since it has one inflow (the Indus river) and several outflows (standard gates, undersluice gates and head regulator gates that were described in the previous subsection. The pond area is known very-well and depends upon the water-level in the pond. In normal operating point the pond area is approximately 10^7 m^2.

The forebay pond model has one influx (the tail regulator gate discharge) and two discharge fluxes: the turbine flow and siphon intake to spillway. The turbine flow is determined by the required power of the plant. The siphon characteristic is given in [2] – the siphon discharge depends upon the forebay water level. To realise the model of the forebay pond level, only the area of the pond needs to be known. This area depends upon the position of the south and north pond gates, and these gates can only be opened or closed.

4 Electrical model

The "electrical" part includes the model of five turbines and corresponding units and the model of the high-voltage switchyard. This model is much more extensive than the "hydrodynamic" part, but on the other hand the underlying models were drastically simplified, i.e. the "electrical" part of the plant was modelled as a static system since its dynamics are very fast compared to the dynamics of the "hydrodynamic" part. Slight exception of this rule is the simulation of the starting procedure of the turbine that was modelled as an automaton, i.e. the next phase in the procedure starts after the completion of the previous one.

As already mentioned, there are five (almost) identical turbines operating in the system. Each turbine has many analogous signals, e.g. governor accumulator pressure, stator winding temperature, excitation current etc. For these signals very simple models (usually of the first order) have been built where the dependence upon the obvious input signal has been taken into account.

What is very important for the staff in the plant, is the possibility to run the HPP or stop it. To run the plant, a sequence of events has to occur. Each step can proceed if all the conditions for the next step have been met. These procedures have been modelled as automata.

The third important part of the HPP model is the model of the control and supervisory system. The control and supervisory algorithms were of course available and they only needed to be transformed to the appropriate form. It needs to be stressed here that high-level automatic modes were not simulated since they provide no value for the training purposes – the operators do not interfere into the system in the fully automatic mode.

5 Conclusions

The paper deals with modelling issues of the HPP Ghazi-Barotha, Pakistan. The plant was modelled for the purpose of building the training simulator. The design of simulator has proven successful since the project was completed successfully. The results of the model are surprisingly good if we take into account all simplifications and many unknown parameters. It was realised during the project that much more effort should have been put to the choice of signals and modelling before the building of the simulator has started. Anyhow, all the problems were circumvented successfully and a stable program was obtained that will hopefully prove efficient for the training purposes.

6 References

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