Simulation of the Guadalupe Hydro-Electric Chain

Aidan Foss, ANF Energy Solutions Inc., Ottawa, Canada.
Reid Boutot, Kenneth MacAulay, ABB Inc., Burlington, Canada.
Dario Alfonso Perdomo Fontalvo, Juan Carlos Molina, EPM, Columbia

Abstract

This paper describes the development of a dynamic simulation of the Guadalupe Hydro Electric Complex, including an integrated control system upgrade for optimization of chain performance. The purposes of the simulation were operator training, performance forecasting, and verifying the robustness of the improved chain control strategy.

The Guadalupe chain belongs to the utility company Empresas Públicas de Medellín, E.S.P in Columbia, and consists of three hydro-generating stations all sharing the same watercourse: Troneras (42 MW), Guadalupe 3 (270 MW) and Guadalupe 4 (216 MW). In addition, there is a bypass valve at Troneras which operates at particular high-flow conditions. The control system was composed of an overall chain controller that interfaced to three individual site controllers. The chain controller consisted of a generic steady-state hydro-chain optimization program that interfaced to application-specific hydro-chain control logic.

The simulation included dynamic models of the main components of the process, covering the bandwidth of interest, together with an appropriate representation of the control system. The process model included dynamic models of the generators, reservoir levels and water transport delays, together with accurate steady-state component characteristics that included hydraulic losses.

For the selection of the simulation environment, a key aspect was linking of the process model to the generic optimization program. Following a survey of different simulation environments, Microsoft Excel was chosen on account of its versatility, performance, user-interface and cost-effectiveness. The final hydro-electric chain simulation included a compiled copy of the optimization program, and ran at approximately 30 times real-time on a laptop PC.

1 Introduction

The Guadalupe Hydro-electric Chain Complex in Colombia consists of three hydro-generating stations all sharing the same watercourse (figure 1.1):

- Troneras, consisting of two 21 MW units and a bypass valve for operation at particular high-flow conditions. In operation since 1964.
- Guadalupe 3, consisting of six 45 MW units. In operation since 1966
- Guadalupe 4, consisting of three 72 MW units. In operation since 1985

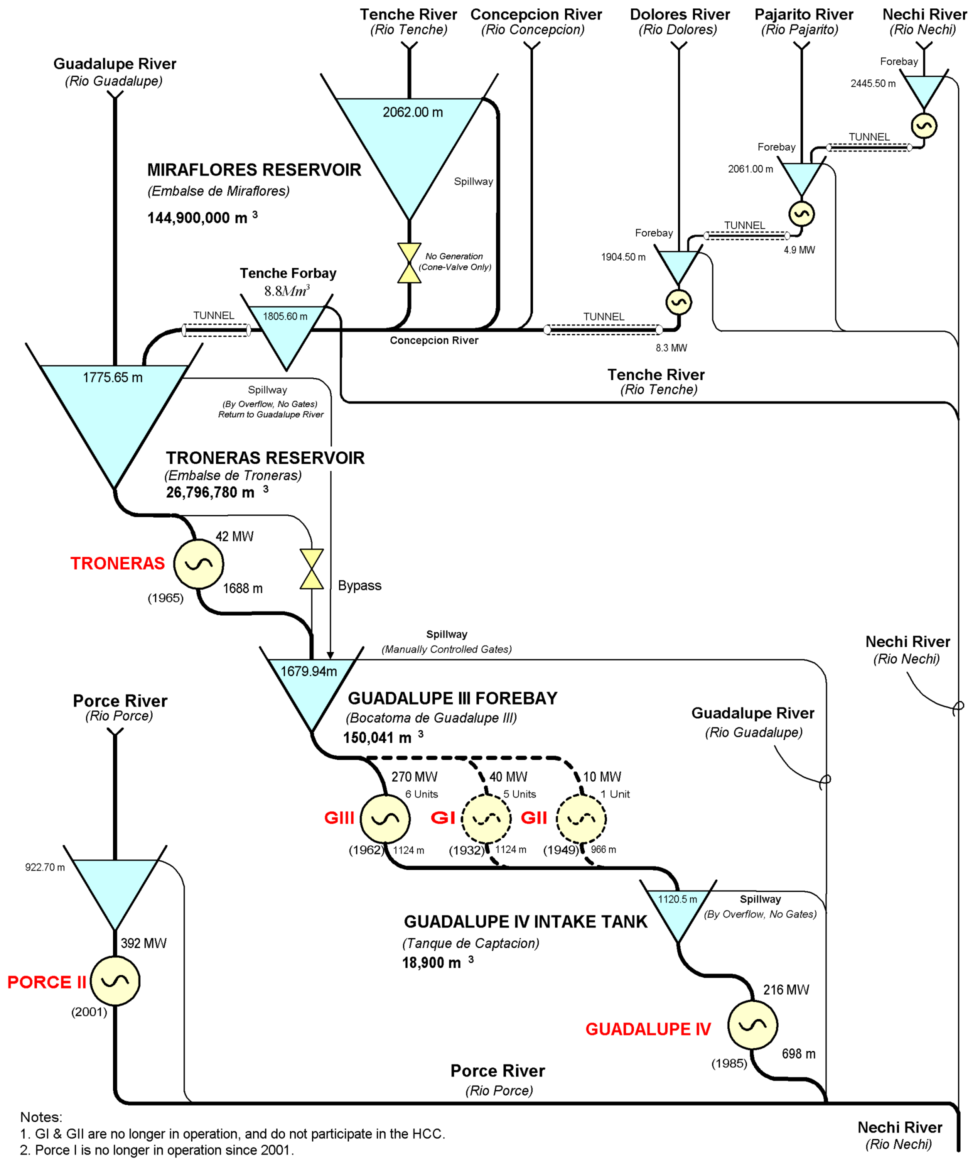

Figure 1.1: Guadalupe Hydro Power Generating System

At the top of the Guadalupe chain is the seasonal Miraflores reservoir with a capacity of 145 Mm^3 on the Tenche River. This, combined with several collector systems on the Concepción River feed Troneras, the first intake reservoir of the complex. This reservoir, which is approximately 1775 m above sea level and with a capacity of some 27 Mm^3, supplies all of the water used for power generation in the three plants of Guadalupe Complex. From the Troneras power plant, the water flows via the Guadalupe River to Guadalupe III power plant and then finally to the Guadalupe IV power plant. The down stream reservoirs in the chain are small, approximately 0.15 Mm^3 and 0.02 Mm^3 respectively.

The difference in reservoir levels between the plants is about 1100 m from Troneras down to the tailrace level of Guadalupe IV. The water travel time is about 10 minutes from Troneras to Guadalupe III and about 30 seconds from Guadalupe III to the intake of Guadalupe IV.

The Guadalupe hydro-electric chain complex, with its 528 MW of generation capacity contributes about 4% to Colombian's overall electric capacity of 13560 MW.

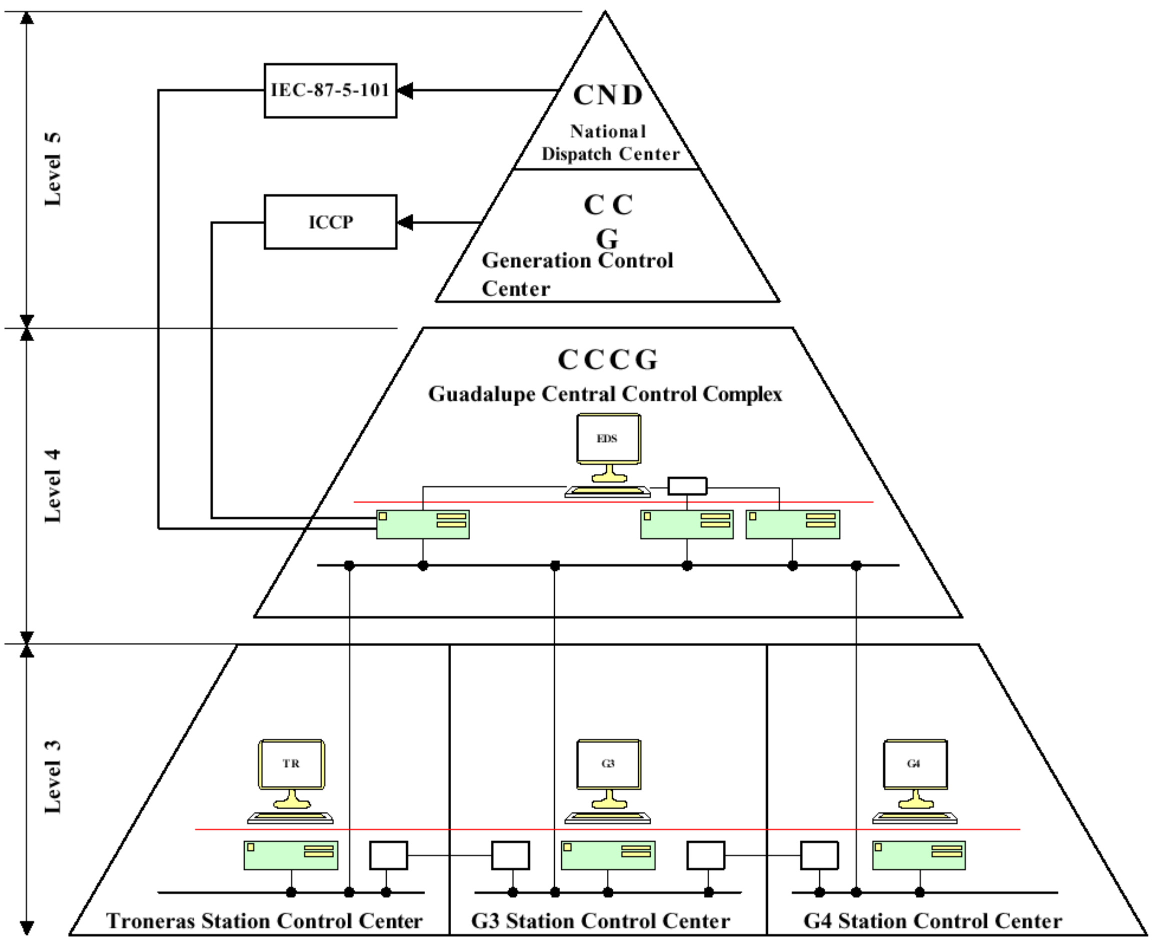

Figure 1.2: Guadalupe Hydro Chain Control Hierarchy

Since November 1988, an ASEA control system has been in operation for short term planning and optimization of the chain [1]. In order to further optimize the performance of this chain, ABB Utility Automation Division were contracted by the station owners Empresas Publicas Medellin E.S.P. (EPM) to upgrade the ASEA equipment with an integrated control system capable of minimizing water usage whilst maintaining all reservoir levels within prescribed limits. The upgraded control system comprised three site controllers operating in conjunction with an overall hydro-chain controller (see figure 1.2).

The hydro-chain controller contained a number of operating modes:

- Base Power Generation (BPG) based on a daily schedule with 24 hour load demands for the hydro-chain
- Regulation Power Generation (RPG) based on a continually updated chain target load demand
- Various alternate and lower level manual modes

As part of the supply, EPM required a dynamic simulation of the overall system in Base Power Generation mode for the purposes of forecasting and operator training. During this mode, a daily schedule comprising 24 hour load demands is passed to the hydro-chain controller. From this, the hydro-chain controller in combination with the three site controllers determines at regular intervals the load demands for the individual units, including the setting of the Troneras by-pass valve (see Figure 2.1). This paper describes the development of the simulation.

2 Simulation Development

In developing a simulation, key stages are [2,3]:

- **Establish the requirements and scope of the simulation:** In this case, the requirement is for forecasting and operator training of the overall system when in Base Power Generation mode. In particular:
    - Graphical display of responses to step changes in the total chain demand
    - Graphical display of responses to unit failures
    - Textual display of key variables
    - Simulation run control
    - Setting of initial conditions (includes reservoir levels, total chain demand and site controller settings)
    - User-friendly operation

- **Identify the bandwidth of interest:** Attempting to cover too much bandwidth can result in unnecessary complexity and slow simulation run times. Generally, the shortest time-constant in a model identifies the calculation iteration period, whilst the longest time-constant determines the duration for which the simulation needs to be run. From knowledge of the bandwidth of interest and a thorough understanding of the system to be modeled, the model equations and their underlying assumptions are then derived.

- **Select the simulation environment:** It is generally important to determine the simulation environment early on in the design process as this can place important restrictions on the implementation of the model equations. Key considerations were an efficient interface to the generic hydro-chain optimization program and transportability of the simulator to the end-user.

2.1 Identifying the Bandwidth of Interest

Prior to considering bandwidth, the system to be modeled is first reviewed. The system involves (see Figure 2.1):

- The hydro-chain controller, which consists of the generic steady-state optimization program called the Economic Dispatch Solver (EDS), and application-specific hydro-chain control logic referred to as the Hydro Chain Control (HCC). Together, these determine the optimal settings of all units under both steady-state and dynamic conditions.

- Site-controllers, with the capability to specify whether a unit is on or off, and whether it is operating independently or as part of the optimized hydro chain control.

- The hydro chain involving all generators, discharge flows, flow transport delays and reservoirs.

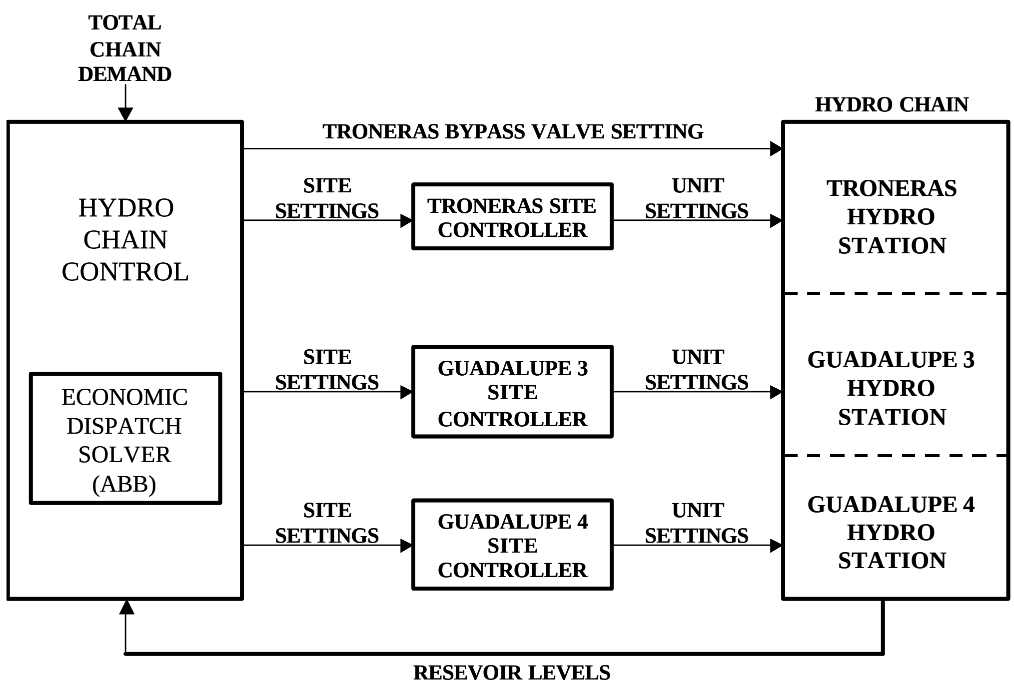

Figure 2.1: Guadalupe Control Strategy Overview

Key bandwidth considerations are:

- In Base Generation Mode, (which is the scope of the simulation), total chain demand set-points are updated hourly.

- The EDS optimization program is executed once per minute. This calculation forms part of the control laws associated with the regulation of reservoir levels and the operation of the Troneras bypass valve.

- The Hydro Chain Control and the three site controllers can be considered as operating continuously. The HCC contains dynamic components with time-constants chosen to match the water transport delay times.

- The water transport delay times between sites were given as:
    - Troneras to Guadalupe 3: 600 seconds
    - Guadalupe 3 to Guadalupe 4: 30 seconds

- To gauge the response times associated with reservoir level dynamics, the reservoir discharge times assuming no inflow and maximum outflow were calculated:
    - Troneras Reservoir: 9000 minutes
    - Guadalupe 3 Forebay: 50 minutes
    - Guadalupe 4 Intake: 6 minutes

- A typical response time of the generators to changes in unit load setting was given as 10 seconds.

Accordingly, it was chosen to ignore dynamic effects with frequencies of 0.5 Hz or higher, for instance associated water hammer or voltage transients. The generators were to be modeled as first order lags, and an integration update period of 1 second used throughout the simulation. Although this would introduce some one-second delays in the model, (e.g. between a unit failing and the site controllers becoming aware of this failure,) this was considered acceptable.

2.2 Model Equations

The various components of the model, whose interactions are shown in Figures 2.1 and 2.2, are described below.

2.2.1 Total Chain Demand

It was decided only to model changes in the total chain demand that were co-incident with a call to the EDS optimization program. Since demand changes occur at most hourly in Base Generation Mode, and calls to the EDS optimization are performed each minute, this was considered acceptable, and reduced the amount of HCC logic that would need to be implemented (see 2.2.3)

2.2.2 Economic Dispatch Solver

A compiled version of the Economic Dispatch Solver (EDS) program was used.

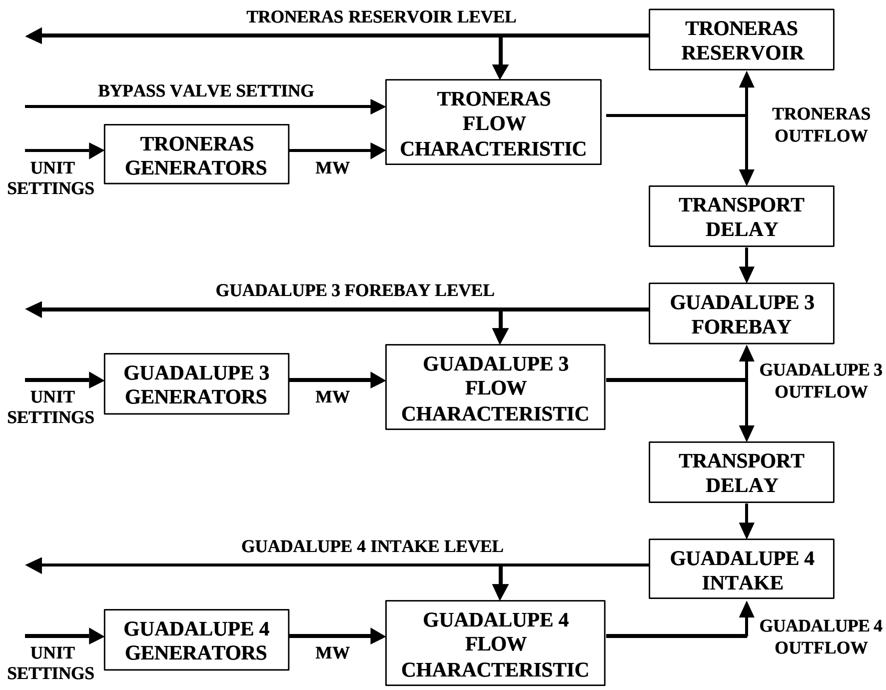

Figure 2.2: Guadalupe Hydro Chain Model

2.2.3 HCC Logic

Only those parts of the HCC logic associated with Base Generation Mode were considered. In addition, the parts of the HCC logic associated with a change in the total chain demand in-between calls to the EDS were ignored. The main parts of the HCC logic that were modeled were:

- Reservoir level range limits
- Control laws associated with the regulation of reservoir levels and the operation of the Troneras bypass valve.
- Capacity checks based on the total chain demand
- Delays and rate limits applied to outputs from the EDS to the site controllers

2.2.4 Site Controllers

The site controllers allocate power set-points to each of the generating units at their site. The site controllers can be used to specify:

- whether a unit is on or off
- whether a unit is acting independently or as part of the overall optimized chain control.

At least one unit at each site must be on and acting as part of the overall optimized chain control.

2.2.5 Generators

The dynamic responses of the generators were modeled as first order lags. Each unit was assumed to have a time-constant of 10 seconds. A facility was included to enable the user to independently fail units at user-specified times.

2.2.6 Site Discharges

The site discharge/power and discharge/valve characteristics were the supplied steady-state characteristics, which included hydraulic losses. Tailrace levels were assumed constant with spill flows assumed to be zero.

Under most initialization conditions, the EDS allocates generator settings corresponding to equal discharges from all three sites. The Troneras reservoir inflow was constant throughout a simulation run, and set equal to the initial Troneras outflow.

The inter-site transport delay times were fixed, with the initial inter-site flows set equal to the discharge from the upstream site.

2.2.7 Reservoir Level Variation

The rate of change of reservoir level is calculated from the flow mismatch and reservoir surface area:

$$d(\text{level})/dt = (\text{flow\_in} - \text{flow\_out}) \,/\, \text{surface\_area}$$

3 Simulation Implementation

A range of simulation environments was considered. Key requirements were:

- Ability to interface to the EDS optimization program
- Ability to readily implement the model equations
- User-friendly user interface with:
  - Graphical display of responses
  - Simulation run control
  - Initial condition data entry
  - Textual display of key outputs
- Readily transportable to the end-user
- Low life-cycle cost

Previous experience had demonstrated that Microsoft Excel with its inherent Visual Basic for Applications (VBA) programming capability could be configured as a low-cost transportable environment for dynamic simulation [4]. The user interface requirements can be met with the Excel spreadsheet, whilst the model equations can be implemented in VBA.

In particular, the standard Windows PC operating environment offered a straightforward method for interfacing with a compiled implementation of the EDS optimization program through using OPC (**O**bject Linking and Embedding for **P**rocess **C**ontrol) linking software. The overall simulation implementation structure is shown in Figure 3.1 and the resulting user-interface in Figure 3.2.

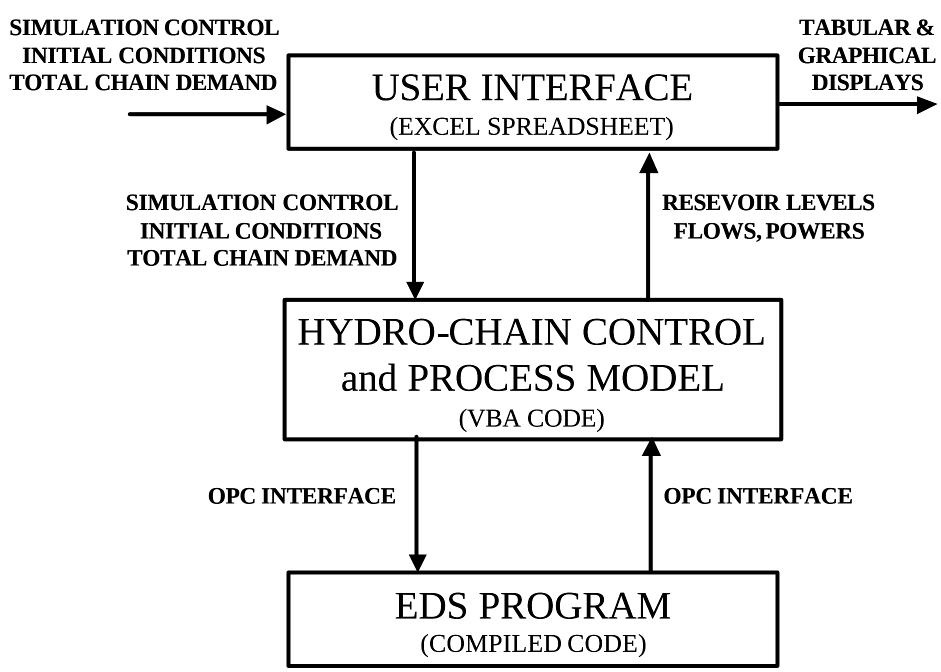

Figure 3.1: Simulation Implementation Structure

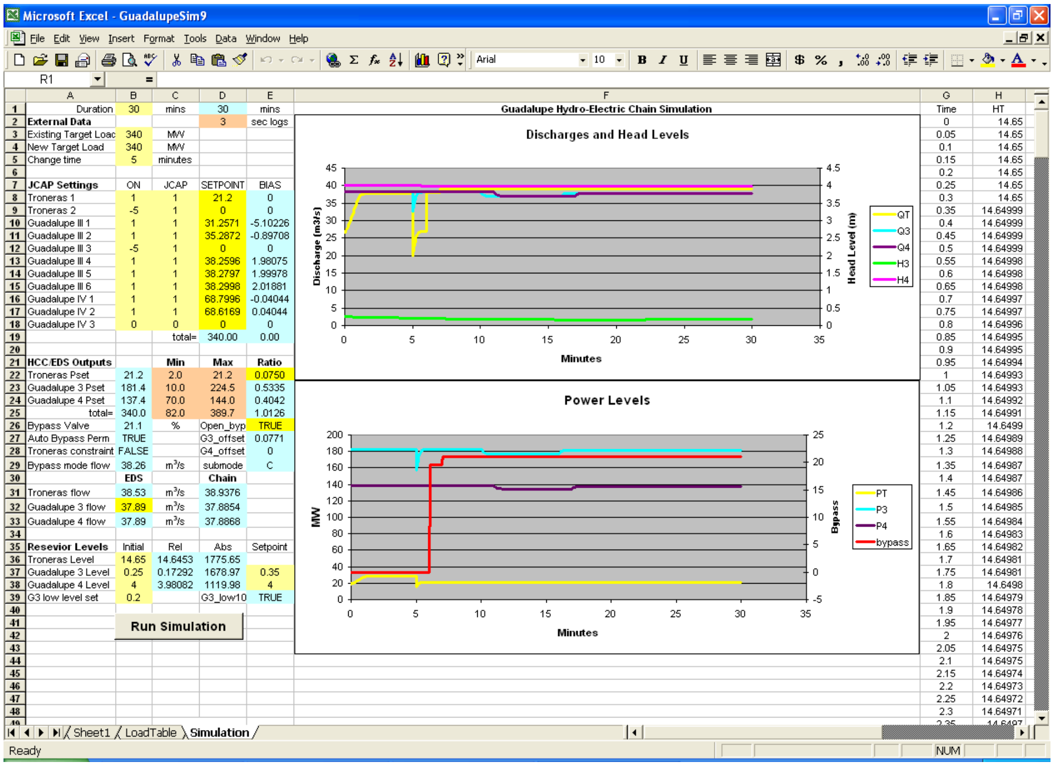

Figure 3.2: Simulator User Interface

The simulation utilized two update periods:

- 1-second: for equations associated with the hydro chain process, the site controllers and the portions of the HCC associated with inputs to the site controllers.
- 1-minute: for calls to the EDS program and to the portions of the HCC associated with the calculation of inputs for the EDS program.

3.1 Simulator Performance and Verification

The simulation on a laptop PC ran at approximately 30 times real-time, which was more than sufficient for the requirements of operator training and forecasting.

A range of verification tests were carried out using the simulator, covering step changes in the target chain load and unit failures. All the responses matched the results expected from the full hydro chain control system.

Not only was the development cost low, but there were minimal licensing and delivery issues. The simulator consisted of a laptop PC with Microsoft Excel, an Excel file occupying less that 400kB (covering the user interface and equations), and the EDS optimization program with appropriate OPC links.

In addition to operator training and forecasting, the simulator can be used for what-if studies and for the rapid evaluation of future proposed algorithm enhancements.

4 Conclusions

A dynamic simulation of the Guadalupe Hydro Electric Complex in Colombia has been developed for the purposes of operator training and forecasting. The simulation includes relevant portions of an ABB-supplied integrated control system for minimizing water usage whilst maintaining reservoir levels within prescribed limits.

Key stages in the development of a successful simulation are:

- Establish the scope and requirements of the simulation
- Identify the bandwidth of interest, and from this derive the model equations
- Select the simulation environment

Through applying these principles, a versatile low-cost simulator was developed. The simulator included:

- dynamic models of the generators, reservoir levels and transport delays
- accurate steady-state component characteristics including hydraulic losses
- a compiled copy of the ABB generic hydro-chain optimization routine
- appropriate portions of the Guadalupe application-specific control logic
- user-friendly interface with graphical displays

The simulator consisted of a laptop PC with Microsoft Excel, an Excel file occupying less that 400kB (covering the user interface and equations), and the ABB generic optimization program. The simulator ran at approximately 30 times real-time. In addition to operator training and forecasting, the simulator can be used for what-if studies and for the rapid evaluation of future proposed algorithm enhancements.

5 References

[1] K N Zadeh, J H Villada, A Weibull, "Operation Planning and Control of Cascaded Hydro Plants" IEEE Transactions on Power Systems, Vol.6, No.2 May 1991.

[2] A M Foss, "The Simulation Life-cycle", IEE Colloquium on "The Use of Simulation in Control System Design", December 1986.

[3] A M Foss, "Towards a general procedure for dynamic model development", Institute of Measurement & Control Conference & Proceedings, 1988.

[4] A Foss, Y Grandmaitre, W Kemp, D Van Spengen, M Diamond "Tools and Structures for the Application of Micro-Controller Technology to Small Hydro Automation", Presented at HydroVision 2004, Montreal, August 2004.

Authors

Aidan Foss PhD, P.Eng. has over 28 years of professional engineering experience. A graduate in mathematics from Cambridge University with a doctorate in turbine control from Imperial College, Aidan specialized in computer control and was Vice-Chairman of the United Kingdom Simulation Council. Through the National Grid Company, Aidan focused on power applications, including auditing and modeling of generator control systems. As the Principal Engineer of ANF Energy Solutions Inc., Aidan provides technical consultancy services covering power-plant automation, generator-grid interconnection, power systems analysis and power quality.

Reid Boutot, C.E.T. is a Senior Systems Integrator for BU Power Plant Automation BU, Asea Brown Boveri (ABB) Inc. in Burlington Ontario. Reid is specialized in the design and implementation of Hydroelectric, Combined Cycle, Geothermal, and Cogeneration Power Plants as well as start-up and commissioning. He is presently stationed in Burlington Ontario, under the PTUA division and currently doing R&D for hydraulic turbine control, governing and optimization applications.

Kenneth MacAulay, P.Eng. is an Analog/modulating/optimization Application Supervisor for Power Plant Automation BU, Asea Brown Boveri (ABB) Inc. in Burlington Ontario. Ken has many years experience in power plant control for Hydro, Thermal, combine cycle plants.

Dario Alfonso Perdomo Fontalvo, P.Eng. Is a senior project manager for the Generation Engineering Area at Empresas Públicas de Medellin. He received his B.S. degree in Instrumentation & Control Engineering from Instituto Politécnico Jaime Isaza Cadavid (Columbia) with a M.S. degree in Physics from Universidad de Antioquia (Columbia). Currently he is a Ph.D. student in Electrical Engineering at Universida Politécnica de Valencia (Spain).

Juan Carlos Molina, P.Eng, is the Chief of Metropolitan Generation Area of Empresas Publicas de Medellín E.S.P (Columbia). He is an Electrical Engineer from Universidad Pontificia Bolivariana (Colombia) with a Master in engineering degree in Control and Automation Systems from Universidade Federal de Santa Catarina (Brasil). He has worked like Operation and Maintenance Engineer and Manager of other Hydroelectric Power Plants and has been Coordinator of Modernization and Upgrade Projects of Hydro Plants of EPM. He participated in the conceptual design and specifications of the equipments included in the Guadalupe Upgrade Project.