OPTIMAL CO-ORDINATED CONTROL OF HYDROPOWER PLANTS

Thomas Rauschenbach *

* *Fraunhofer Applications Center for System Technology*
Am Vogelherd 50
98693 Ilmenau/Germany
e-mail: thomas.rauschenbach@ast.iitb.fraunhofer.de

Abstract: River hydropower plants must accomplish several tasks. They have to generate electric energy, guarantee the navigation and reduce the extent of a flood if possible. If there is a cascade of hydropower stations in a river, then it is not possible to solve these tasks with a decentralized control strategy optimally. One is faced with a multiple criteria optimization problem. This contribution presents a strategy for the optimal multiple criteria control of cascades of river hydropower plants. For this purpose a simulation and control toolbox was developed for MATLAB/SIMULINK©. The application of this toolbox is shown at the example of the optimal co-ordinated control of four hydropower plants at the Austrian Danube.

Keywords: Optimal control, co-ordination, power station control, simulation

1. INTRODUCTION

A simulation model is always a precondition for the optimal design of an automatic and/or automatized control of reservoirs in rivers. This applies to both, the control in accordance with operating rules as to the coordinated control of a cascade of reservoirs (Cuno, 1985), (Jensch, 1986), (Marenbach *et al.*, 1995), (Fäh, 1987), (Rauschenbach, 1996), (Rauschenbach *et al.*, 1998), (Nestmann and Theobald, 1994). The software tool ILM-RIVER was developed for this purpose. It consists of the modules "RIVER-MOD" and "RIVER-CON". The HR-models were developed for this particular case of application. They are especially well suitable for the design and the verification of control strategies. A precondition for its effective application is the possibility to build a model for a river section in a short time. Therefore, for each of the developed models a simulation block was constructed as part of MATLAB/SIMULINK©. These simulation blocks are combined into the library "RIVER-MOD". With the aid of a graphic editor, it is straightforward to build the entire model for one or more reservoirs. Integration of control concepts is required for the simulation. The control according to operating rules was implemented. In addition, further control concepts are integrated. These are: 1) the coordinated control for improvement in flood control and 2) a strategy for smoothing of discharge. These control blocks were combined into the library "RIVER-CON". These libraries resulted from studies of the design of new control strategies for the reservoirs of Danube Hydropower Austria in Vienna.

2. MODEL LIBRARY "RIVER-MOD" FOR RESERVOIR MODELLING

The simulation of behavior of a reservoir prerequisites an analytical description. For control, it is sufficient to know the behavior at gauges for water level and flows. Up to now the design of control concepts is done with models of control technology or black-box-models. They cannot describe instationary behavior with sufficient accuracy. Models on the basis of the Saint-Venant-equations can meet these demands better. However, they are not suitable for an on-line optimization, because the solving of the differential equations system requires a lot of computational time. Furthermore, it is difficult to simulate overflow regions and backflow behavior. For this reason, a synthesis of both models was developed, the new HR-models. These models meet these demands with respect to accuracy and simulation speed (Fichtischerer, 1965). The aim of modeling a river section is to determine the flow and water level at gauges, which are important for control. For this purpose, all characteristic features in a river course must be considered. First of all, in case of stationary and instationary behavior, e.g. by an increasing flood wave, models which compute flow and water level must be available. Otherwise, no satisfactory simulation is possible. Further models are necessary in addition to these models. As first the model of backflow. At narrow places in the river course, there are backflows into the bordering fields. As a result, the behavior of flow and water level is modified. Secondly the model of overflow regions. While attaining a defined water level a part of the river runs into overflow regions. Therefore, the flow behavior in these regions must be described. In this case usually the water does not run through the next power plant and so the balance of flow is not correct. This complicates the modeling. Pumping stations in these regions and incoming flows from creeks must be considered too (Maniak, 1992), (Bollrich and Preißler, 1992), (Dyck, 1978).

3. MODEL LIBRARY "RIVER-CON" FOR RESERVOIR CONTROL

3.1 Introduction

Reservoirs are constructed with the aim to use the environment-friendly hydropower for generation of electric energy. In most cases, this fact leads to the building of reservoir cascades in rivers. These influence one another by hydraulic link-up. As a result, natural flow behavior is strongly influenced. Reservoir cascades have further tasks in addition to energy production, e.g. avoidance of overflows and guarantee of navigation. The energy production must be subordinate to these tasks in order to prevent a danger to people and real values. To solve these tasks, operating rules were determined. Two modules were developed for the realization of the operating rules. These comprise of a conventional PID-concept and the Fuzzy- concept FUGERA. These concepts cannot optimally solve the mentioned multicriterial tasks. Therefore, a newly developed MEFURO-concept is presented. Furthermore, a module for smoothing of discharge was integrated (Rauschenbach *et al.*, 1998).

3.2 Modules of the library "River-Con"

The above-mentioned modules are combined in the library "RIVER-CON". Subsequently, the individual modules are presented in brief.

(1) *PID-concept*
This module realizes a control of water levels with prescribed set-points. These water levels must be controlled situation-related at spatially separated gauges. Recognition of the situation occurs with the aid of the water levels. After that the corresponding PID-controller is activated.

(2) *Fuzzy-concept FUGERA*
The concept is used to solve the same task as the PID-concept. Unlike the PID-concept one controller is used for all control situations. This controller is a Fuzzy-adapted PID-controller. A Fuzzy system determines context-related the controller parameters. The situation is characterized by the water levels in the reservoir. The input of the controller is a total control error. This error consists of the weighted sum of the partial control error of each situation. Another Fuzzy system determines the weighting factors depending on the situation. One achieves with it an improvement in behavior when crossing over between different situations. Furthermore, an improvement in robustness against disturbances is achieved.

(3) *MEFURO-concept for optimal coordinated control of reservoir cascades*
Activation of this module occurs after a predicted flood situation. The task of the coordinator is the computation of optimal set points for the sub-controllers at each hydropower plant. Aims of control are:
- Best possible flood control by minimizing the maximum discharge of each reservoir in the cascade. for water levels.
- Prevention of limit violations.
- Transfer from normal operation to flood control with maximum energy output.

The input of the coordinator is the predicted incoming flow of cascade and the current state of each reservoir (water levels and flows). The computation of the control trajectory is done for the power stations with the aid of an optimization criterion (see Fig. 1). The optimization criterion is situation-related (Rauschenbach *et*

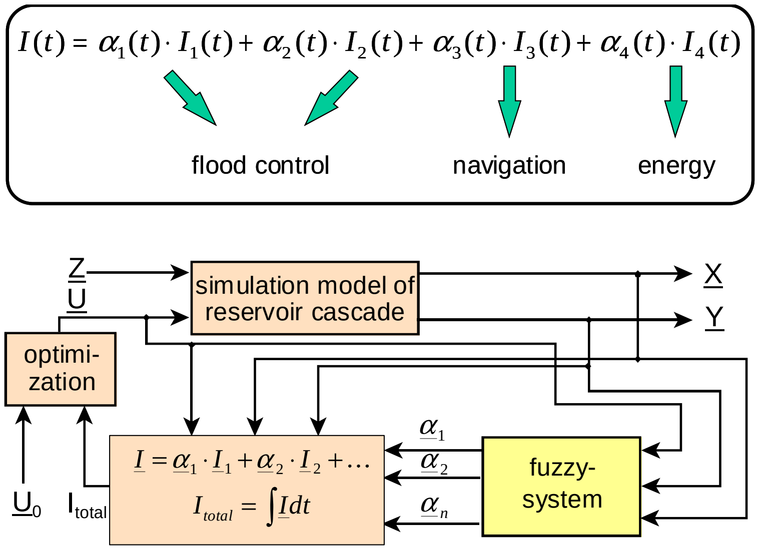

Fig. 1. Principle of multiple criteria Fuzzy aided optimization. Used vectors: $\underline{\mathbf{I}}$ - goal function, $\underline{\mathbf{U}}$ - manipulated variable, $\underline{\mathbf{U_0}}$ - initialization of manipulated variable, $\underline{\mathbf{Y}}$ - output (water level, flow), $\underline{\mathbf{X}}$ - state vector, $\underline{\mathbf{Z}}$ - disturbance input and $\underline{\alpha_i}$ - weighting vector.

al., 1998), (Neumüller and Bernhauer, 1969), (Kühne, 1975), (Meisel, 1994), (Allmer, 1998), (Rauschenbach, 1998). Each of the tasks mentioned above is considered by one partial criterion in the optimization criterion. Every partial criterion is weighted by a factor. For the first time these weighting factors are computed by a Fuzzy system situation-related. The optimization is iteratively carried out. That means the optimization is started again after an updated forecast or a change of states inside the reservoirs. One receives an adapted control trajectory as a result. The Simplex-method and evolutionary algorithms are used as optimization procedures. It is portable to several reservoirs.

(4) *Control-concept for discharge smoothing*
Finally the concept for discharge smoothing is presented finally. The aim is to minimize the discharge ups and downs. In this case, the tolerance limits of the water levels must not be exceeded. A Fuzzy system is used for this control task. In addition to the water level, the gradient of the incoming flow is also taken as an input to the Fuzzy-system.

4. SIMULATION MODEL FOR DANUBE RESERVOIR YBBS

On the basis of the above-described modules, the simulation model for the Danube reservoir Ybbs is presented (Rauschenbach, 1998). Main aim is the modeling of the dynamic behavior of the flow section between the two hydropower plants Wallsee and Ybbs. The model must describe the real incoming flow behavior, real discharge behavior as well as the water level trajectories. Fig. 2 shows the river section in consideration.

Characteristic information for this river section: The river length in the reservoir Ybbs is approx. 34 km. Distances: Sarmingstein - Ybbs: 13 km, Ardagger - Sarmingstein: 12 km, Wallsee - Ardagger: 9 km and Bottom slope: $3,4 \cdot 10^{-4}$. River width at normal water levels: 150m - 1000m.

Behind the gauge Au (in the middle of backwater area) a part of the water passes by the hydropower station Wallsee at flows larger than 6000 m^3/s. Therefore, the downstream gauge does not register the total incoming flow to the reservoir Ybbs. For this reason, it is necessary to consider the effect of "passing by" in the model. The activation of the retention rooms occurs with the aid of floodgates and pumping stations at a Danube-flow of 4700 m^3/s. With a flow of 5400 m^3/s, the water pours directly into the retention rooms. Fig. 3 shows the rough model of the reservoir Ybbs.

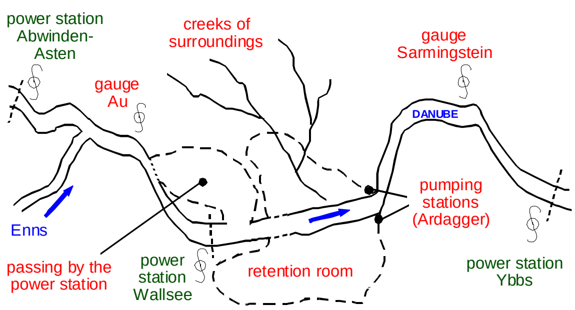

Fig. 2. River section between hydropower stations Abwinden and Ybbs

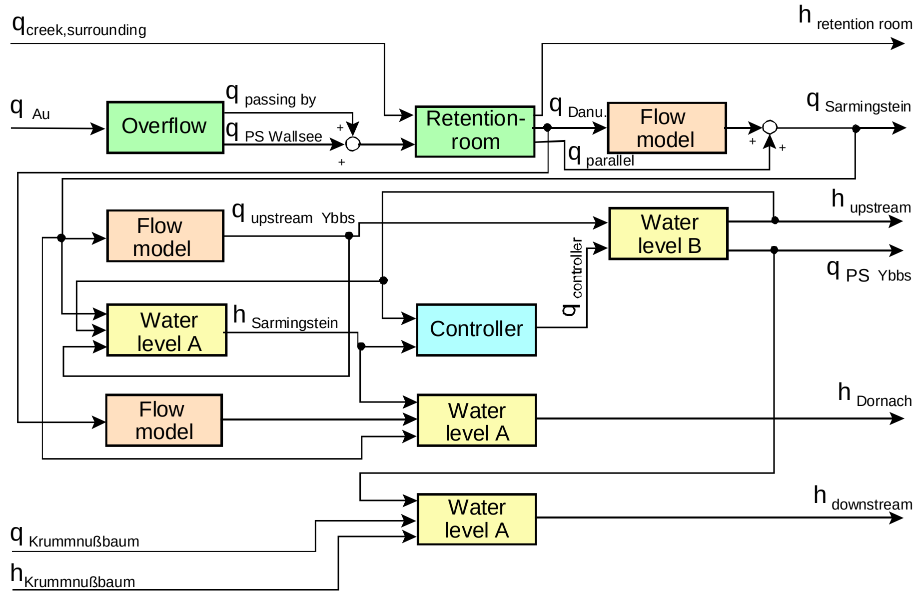

Fig. 3. Model for reservoir Ybbs

Good results are achieved with this model in all flow ranges. Fig. 4 shows the result for the discharge of the hydropower station Ybbs during the flood of July 1993. The errors of the water level-models are also small. Here the error is only a few centimeters. Respectively simulation models for three further reservoirs were developed, for Abwinden, Wallsee and Melk. The modeling error is similar for all of them.

The simulation duration is 12 seconds for the reservoir cascade consisting of the mentioned four reservoirs (PC with Intel Pentium 4 / 1 Ghz). In this example a flood was simulated with duration of five days. The simulation was carried out with three minutes time steps. These models are a condition for developing a coordinated control for a cascade of reservoirs (Rauschenbach, 1998).

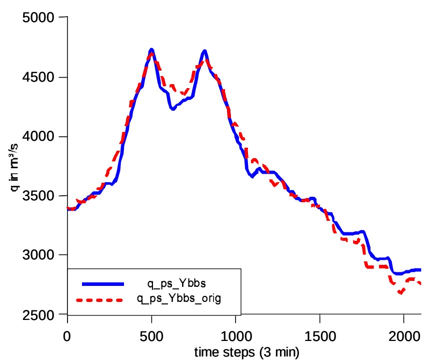

Fig. 4. Results of Flow-Model for flood in July 1993

5. OPTIMAL COORDINATED CONTROL OF FOUR DANUBE-RESERVOIRS

In section 3, the concept "MEFURO" for coordinated control of cascades of reservoirs was presented. This concept was applied to the four Danube reservoirs Abwinden, Wallsee, Ybbs and Melk (Rauschenbach, 1998). The principle of coordinated control is shown in figure Fig. 5. This strategy is based on the theory of hierarchical control. As before, every reservoir has its own underlying automatic controller. These are effective in standard situations and they work according to the "up to now" valid operating rules. The coordinator is activated in the case of a predicted flood situation. In this case, the coordinator computes the optimal discharge trajectories for every hydropower station in the cascade. This new set point data is delivered to the underlying automatic controllers. The coordinator is constantly informed about the current situation in the reservoirs. By exceeding boundary values, control strategy is changed. Fig. 6 shows the results of the new control concept. The maximum of the flood is reduced considerably. The decentralized control of the hydropower plants doesn't obtain this result. Decentralized control doesn't reach any reduction of the flood.

6. CONCLUSION

Two libraries for simulation and control of rivers and cascades of hydropower plants were presented in this contribution. The configuration of a simulation system for a cascade of reservoirs is presented on a practical example for Austrian Danube. A good copy of the real behavior could be achieved with this system . With the aid of the

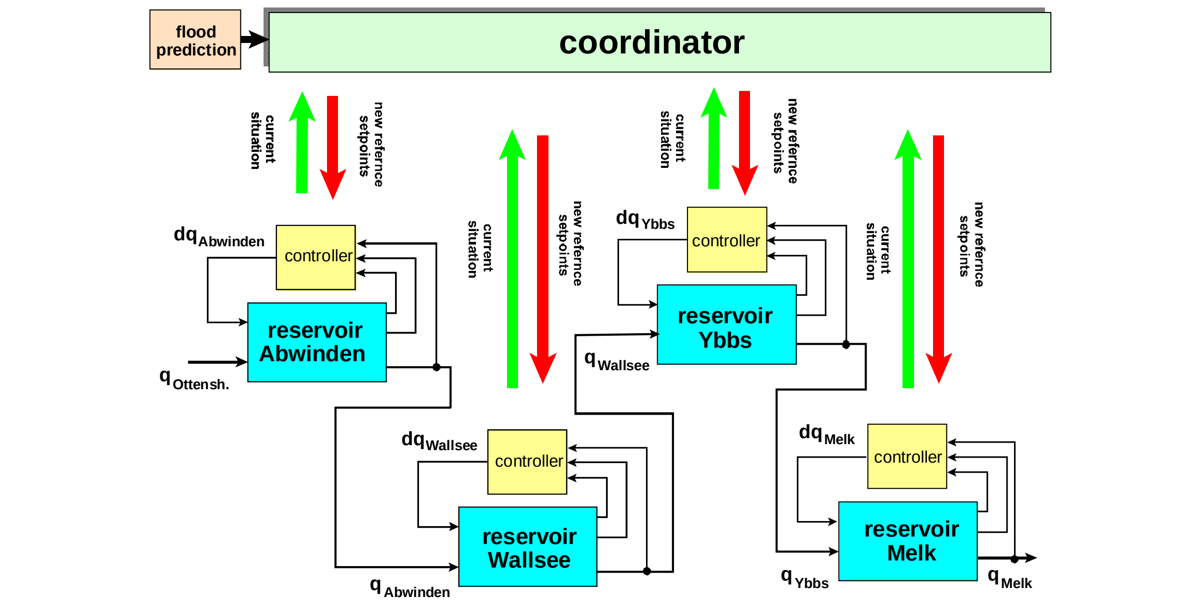

Fig. 5. Principle of coordination

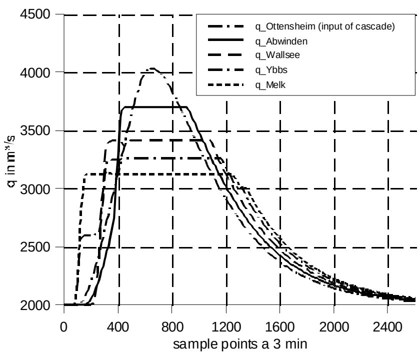

Fig. 6. Results of co-ordinated control

new developed control concepts, an improvement in flood control and energy generation became possible. The mentioned libraries can be further developed at any time(Cuno, 1985).

REFERENCES

Allmer, H. P. (1998). Untersuchung zur Abflussoptimierung an der Österreichischen Donau. PhD thesis. University of Technology Vienna.

Bollrich and Preißler (1992). *Technische Hydromechanik*. Verlag für Bauwesen. Berlin München.

Cuno, B. (1985). Entwurf des Automatisierungssystems für eine Stauhaltungskette. Technical report. AEG. Frankfurt.

Dyck, S. (1978). *Angewandte Hydrologie*. Verlag für Bauwesen. Berlin.

Fäh, R. (1987). Digitale Simulation von Stauregelungen in Flusssystemen. In: *ASIM 4. Symposium Simulationstechnik*.

Fichtischerer, N. (1965). Regelung des Oberwasserpegels an Staustufen. *Wasserwirtschaft*.

Jensch, I. (1986). Kraftwerksautomatisierung an österreichischen Flüssen. In: *SAT GmbH Informationstag*.

Kühne, A. (1975). Stauregulierung an Flüssen. *Wasser- und Energiewirtschaft*.

Maniak, U. (1992). *Hydrologie und Wasserwirtschaft*. Springer Verlag. Berlin Heidelberg.

Marenbach, P., H. D. Bettenhausen and B. Cuno (1995). Selbstorganisierende Generierung strukturierter Prozessmodelle. *at – Automatisierungstechnik*.

Meisel, I. (1994). Steuerung aus der Ferne (Zentrale Betriebsführung von Flusskraftwerken). *Siemens Standpunkt*.

Nestmann, F. and S. Theobald (1994). Numerisches Modell zur Steuerung und Regelung einer Staustufenkette am Beispiel von Rhein und Neckar. *Wasserwirtschaft*.

Neumüller, M. and W. Bernhauer (1969). Stauregelung und Abflussregelung an Laufwasserkraftwerken. *Wasserwirtschaft*.

Rauschenbach, Th. (1996). Untersuchung an österreichischen Donaustaustufen zur Steuerung bei Hochwasser. Die Modellbildung und das Steuerkonzep. In: *Konferenz der Donauländer*.

Rauschenbach, Th. (1998). Eine allgemeingültige Methode zur Modellierung und optimalen mehrkriteriellen Steuerung von Staustufen und Staustufenkaskaden. PhD thesis. University of Technology Ilmenau.

Rauschenbach, Th., J. Wernstedt and H. P. Allmer (1998). Mehrkriterielle koordinierte Prozessführung von Staustufenkaskaden - Pilotprojekt österreichische Donaustaustufenkette Melk-Ybbs-Wallsee. *at – Automatisierungstechnik* pp. 557–564.