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Hydropower Plant Control using Holonic Structure Concept

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Abstract: - In hierarchical distributed control systems for hydro power groups located over a large area, there are requirements for independent (autonomous) operation of control systems for each power group (or parts of the group), to solve local problems or in case of real-time faults over communication paths with upper levels. In this case, the control equipment for power groups may be defined as holons, and their autonomy property ensures a decentralized relationship of heter-hierarchical type. There are presented the possibilities of the study of operational regimes of the plant using experiments performed on lab equipment. This is offering a methodology to implement alternate solutions for the control systems of power plants.

Key-Words: - Distributed control systems, Hydro power plant, Holonic architecture

1 Introduction

The hydro power plant systems using together the potential energy of the same water stream require more and more the use of complex control systems, which have multiple functions such as:

* The local control system at the group level:
- The optimal conversion of hydraulic energy in electric energy in conditions of the variable flow of the water by maintaining the water level in the reservoir at a maximum;
- Maintaining the hydro-generators in the stability area considering the variable turbined debits and balancing the energy in the system;
- The correlation of the turbined debits for the plants installed in a cascade along the river course (the influence of the water propagation);
- The automatic starting and stopping of groups (with the solving of the synchronization and in-phase connection) considering the energy requests and the water available at an optimal use.

* The central control system at the hydro plant level:
- Monitoring, control and data acquisition for operating processes- SCADA systems
- Automatic control of technological parameters;
- Optimisation and coordination of process flows taking place in series, parallel or mixed;
- Resources and production planning according with requirements, including forecasting algorithms;
- Automatic reconfiguration of control systems, both hardware and software, to adapt to the actual operating requirements, both internal and external;
- Fault detection and localization, increasing the fault robustness of the systems and automatic control in fault conditions;
- Real time operation through parallel information processing.

Microprocessor technology evolution, combined with accessible costs and increased reliability allowed the development of new control systems, using distributed structures, multiple operational levels, and having dedicated hardware and software structures. [Popovici 1990, Vinatoru 2000]. Such production systems for hydro energetics, capable to rapidly adapt to market demands, require an evolved control system, which is flexible enough to adapt to new operational demands quick and without major perturbation of the process.

The use of the holonic concept as an instrument for modelling and design of control systems for big distributed processes is based on two properties of holonic structures: autonomy-grants to holons the right to take decisions without consulting an entity from an upper level and cooperation that allows the holons to communicate with other holons to solve some objectives pertaining multiple entities in a holonic structure.

This paper tries to apply this abstract concept to distributed control systems with applications in the hydro power plants and has the following objective: Providing a software flexibility to hierarchical control systems, which will allow a quick adaptation of the technological process and control strategy to the real operating restrictions, fault detection and localization, control in fault conditions, and remote monitoring for spatially distributed systems over large areas (the case of hydro power plants).

2 The concept of holonic structure

2.1 Control architectures utilized

The design and use of advanced process control systems [Tunser Orun.2000, van Brussel, 1998, Borangiu 1995] is defining the control structures for industrial processes:

a). Centralized control systems, one central control (directly control system actuators).
b). Distributed and hierarchical control structures, using multiple functional levels.
c). Hybrid control structure, derived from the b-type structure, with supplementary functions for cooperation and data sharing between controllers located at different levels.
d). The heterarchical control architecture, consists of independent structures called "agents" which execute commands based on their current and future estimated loading.

All these distributed control structures have some deficiencies: significant delays in the information, synchronization problems between equipment and difficulties in the implementation of some functions such as: software and hardware reconfiguration in case of faults, local autonomy of control units for isolated production units (case of hydro power plants).

2.2 The concept of holonic structure

The deficiencies of distributed control systems have led to the research, development and implementation of new concepts such as: Virtual enterprise, Knowledge-based systems, Agents oriented software, Holonic systems [Ulieru 2006, Fletcher 2006]. The use of the holonic concept as an instrument for modelling and design of control systems for big distributed processes is based on two properties of holonic structures: autonomy-grants to holons the right to take decisions without consulting an entity from an upper level and cooperation that allows the holons to communicate with other holons to solve some objectives pertaining multiple entities in a holonic structure. Recent publications introduce the concepts of Model of Holonic Coalitions and Emergence [Ulieru 2006]. Based on these concepts, the hierarchical character of distributed structures is extended to a hierarchy of holonic systems, which establishes, for the entire system of holons, a certain recursive hierarchy or a heterarchy of holons, without a central control, that allows the cooperation to achieve the system objectives.

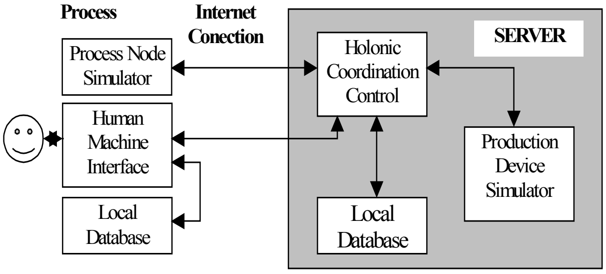


Fig. 1. Holonic structure

2.3 The proposed system architecture

The proposed system architecture, (see figure 2, will have the following components:

- A web-based graphical human-machine interface for the configuration and simulation a process application (provide an access to the remaining components of the system);

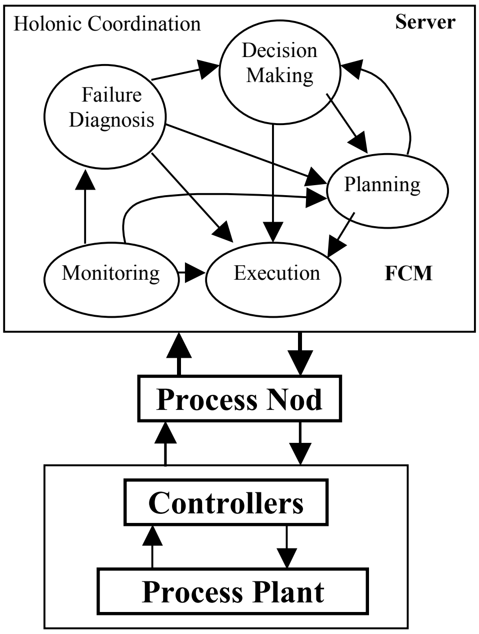


Fig. 2. Holonic Proposed

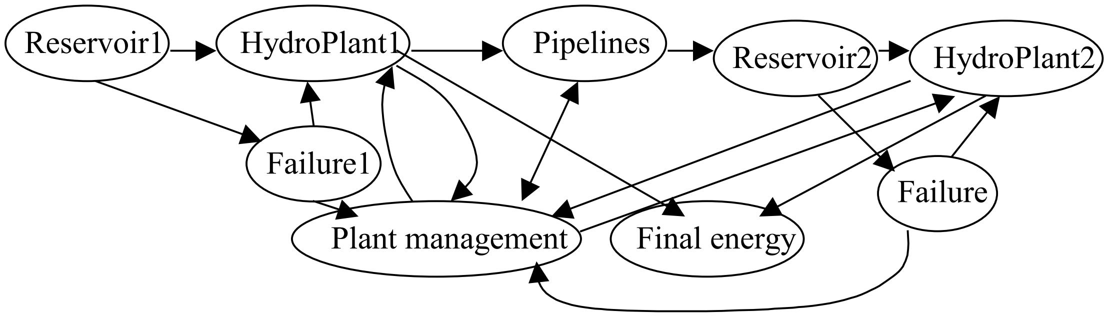


Figure 3. A Fuzzy Cognitive Map Representing the Behaviour of a Hydropower plants

- A local database of alternative scenarios and configurations (experts examine and evaluate);
- A simulation system (performed in operation space) residing at the expert's site capable of simulating the process node, as configured by the expert, using the database.
- A comprehensive database (Energy resources and demand profiles, Energy demands, of power system, Performance characteristics of the plants including capacities, repair and maintenance frequencies, and costs;
- Holonic coordination and control would provide a capability to use distributed communications to enable decision making between various elements of the system, and provide coordination and control of their activities.

This holonic system would have a multi-layered architecture with the lowest level representing the process devices, the middle level representing Process Nodes, and the highest level representing the Management Nod.

2.4 The model elaboration

2.4.1 Hierarchical architecture

Hierarchical architectures are widely used and accepted in enterprise control systems and control systems modelling. (Figure 1). In order to develop advanced modelling methodologies based on soft computing approaches ideas (information theory, neural networks and fuzzy logic) are investigated and utilized to represent and process information in a hybrid and hierarchical industrial system [Medsker 1995]. The proposed methodology is that of Fuzzy Cognitive Maps (FCMs), which can model dynamical complex systems that change in time with non-linear laws.

2.4.2 A Fuzzy Cognitive Map Model

Fuzzy Cognitive Map consists of concepts that illustrate different aspects in the behaviour of the system and these concepts interact with each other showing the dynamics of the system. At the process level of the plant there is a common technical information system for the process control, the computerized and technical management systems that is shared between the production/management teams. The development methodology and features of Fuzzy Cognitive Maps have been presented in some papers.

In this Section a Fuzzy Cognitive Map model for a simple part of a hydropower plant will be developed in order to illustrate the procedure of developing an FCM model for a system and how FCM would look like (see figure 3). The examined example consists of two hydro turbines-generators, which produce the electrical energy using the water from the same river. The pipelines (penstocks and transport canal) connect the two turbines with the reservoir and their status influence both processes as it takes the output of the first group and provides the input to the other but with a time delay. Controllers are used to control these two processes and human operators will supervise and control the whole system.
This FCM consists of seven concepts that represent the main factors, states and variables of the plant.

The FCM is developed by a group of experts who supervise the process and know the operation of the system:

Concept 1: the state of Hydro plant 1;
Concept 2: it represents the state of Pipelines, which connects the two power plants;
Concept 3: the state of Hydro plant 2;
Concept 4: the Final energy Product of the two power plants;
Concept 5: the Quality of the Final energy - Plant management;
Concept 6: the occurrence of Failure 1, mostly related to Hydro plant 1 and water flows;
Concept 7: the appearance of Failure 2, mostly related to Hydro plant 2 and water flows.

The group of experts know the correlation among these concepts and so they can describe the influence of one concept on the other and their causal relationship with a fuzzy degree. First of all, they determine which concept will influence which other. So they describe that are the processes influences, positively or negatively, in comparison with the normal situations.

When experts determined the concepts that consisted the Fuzzy Cognitive Map and the positive or negative influence of one concept on the other, they also had to determine the degree of this causal influence. Every causal relationship among concepts can be represented by a weight. Experts describe the influence of one concept on the other with a linguistic variable. Every expert describes each interconnection with a fuzzy variable and then the corresponding fuzzy weights are combined and integrated into one, which is defuzzified into one numerical weight.

2.4.3 A Hierarchical Supervisory Structure.

The general characteristics of power plants process Systems are their complexity and their large scale construction that make researchers use structural models such as hierarchical, heterarchical and other models in order to model such systems.

In Power Plants Systems framework the human operator offers and supports Supervisory Intelligent Control through the use of a vague control methodology, within which he takes into consideration different factors and their relationship. The proposed structure is depicted in figure 1, where the supervisor is modelled as a Fuzzy Cognitive Map and consists of five sub-FCMs.
Each one of these sub-FCMs accomplishes a special action for the plant at the lower level:

- one FCM is monitoring the plant,
- another one is used for failure diagnosis, the next one is used for decision-making,
- the other for planning actions on the plant
- the last FCM describes the execution commands and sends them to the plant.

These five FCMs are interconnected and they may have common concepts. The plant at the lower level has its own local controllers that perform usual control actions and the supervisor is used for more general purposes: to organize the overall plant in order to accomplish various tasks, to help the operator make decisions, to plan strategically the control actions and to detect and analyse failures.

3 Incorporate Diagnosis into Holonic Systems

3.1 Diagnostic structure

Much of the traditional model of diagnosis is applicable to the holonic systems. The difference being in the distribution of the tasks and the concept of heirarhy. In the holonic systems the diagnostic functions will be integral part of the system and each holon will be responsible for supplying its own health information to the appropriate diagnosis holon. Figure 3 present the generic holon structure with diagnostic functions. A self-diagnosis may commence from the diagnosis holon which will provide data to the database holon, that negotiate with other holons (schedule, process, configuration and diagnosis) to establish parameters for conducting the self-diagnosis.

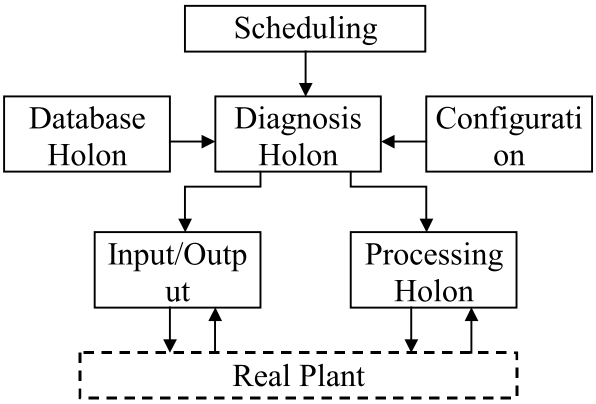


Fig. 4. Diagnostic functions' structure

For example, consider the need for the water pipes holon from figure 2, to test the control valve for flow saturation and to possible leaks along either pipeline section.

The diagnosis holon would determine what required for the test (data and method) and request the I/O holon to monitor flow rate and valve positions, subject to any configuration and scheduling requirement of these holons. In this case it is necessary to wait for time windows to conduct test, to open the algorithm for leak fault detection and reconfigure the water valve if it is necessary.

The processing holon conduct tests and returns data to database holon, which enable comparison of data, collected with the pipeline model and respectively with characteristic flow curve of valve. The diagnosis holon receives the report from processing holon related to the data comparison and he would make the decision about the pipeline and valve health status. If a failed status is determined then the diagnosis holon would be able to establish possible root causes (e.g. leak pipe or valve stitching or saturation) by reference to the database holon.

The local diagnosis holon sends a report to upper level holon (the diagnosis holon from plant management holon). This holon analyses the fault situation and decide the future management strategy (go on or stop hydro group).

3.2 Generic residual generator

The diagnosis holon realises the comparison between real values from the plant and the model values. The residual generator offers the information about possible faults. It is linear discrete dynamic algorithm acting on the observable with the form:

$$R(s) = H_u(s).U(s) + H_y(s).Y(s) \tag{1}$$

that must return zero residuals when all faults are not present. In this case the residual generator will be described by (2):

$$R(s) = H_y(s)[Y(s) - H_{TP}(s).U(s)] \tag{2}$$

were $H_{TP}(s)$ is technological plant transfer function corresponding to command-output canal and $H_Y(s)$ is the FDI controller. We use the PI controller.

For this form of residual generator we propose the implementing structure presented in figure 5.

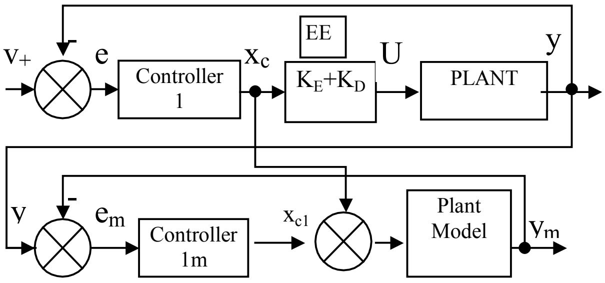


Fig. 5 FDI Structure

For this structure let the plant is described by (3):

$$\dot{x} = f(x, x_c, \alpha); \quad y = C^T.x \tag{3}$$

where is the state vector, y is the measurable output, a is a fault parameter and is the control command

The real controller (PI type to ensure the steady state errors equal with zero), is described by:

$$\dot{x}_c = K_R(\dot{v} - \dot{y}) + K_I(v - y) \tag{4}$$

where v is the set point of the control system.
The control structure for fault detection (fig. 4) includes a plant model described by:

$$\begin{aligned} \dot{\bar{x}}_m &= f(\bar{x}_m, \bar{x}_c + \bar{x}_{c1}, \alpha_m) \\ Y_m &= C^T \cdot x_m \end{aligned} \tag{5}$$

and the control signal:

$$\dot{x}_{c1} = K_R(\dot{y} - \dot{y}_m) + K_I(y - y_m) \tag{6}$$

Replacing variables $\dot{y}\ and\ \dot{y}_m$ in (6) we get:

$$\dot{x}_c = K_R C^T f(\bar{x}, \bar{x}_c, \alpha) - K_R C^T f(\bar{x}_m, x_{c1}, \alpha_m) + K_I C^T(\bar{x} - \bar{x}_m) \tag{7}$$

The FDI control structure, if designed properly, will modify the control signal x_{c1} to obtain $e_{ms} = \lim_{t\to\infty} e_m(t) = 0$.
Therefore,

$$Y_s = Y_{ms} \Rightarrow Y - Y_m = C^T(\bar{x} - \bar{x}_m) \to 0 \tag{8}$$

In this case, considering the steady state regime we get:

$$\lim_{t\to 0}\left[f(\bar{x}, \bar{x}_c, \alpha) - f(\bar{x}_m, \bar{x}_{c1}, \alpha_m)\right] = 0 \tag{9}$$

Using the linear model system (10) of the equations (3) and (5):

$$\begin{aligned} \dot{\bar{x}} &= A \cdot \bar{x} + b \cdot x_c + d \cdot \alpha \\ \dot{\bar{x}}_m &= A \cdot \bar{x}_m + b \cdot x_c + b \cdot x_{ci} + d \cdot \alpha_m \end{aligned} \tag{10}$$

after a few simple transformations in (10) we get the difference between faulty components real α and modelled

$$\alpha_m\text{:}\ \alpha - \alpha_m = \frac{b}{d} \cdot x_{cs} \tag{11}$$

From the precedent analysis it results that the steady state values of controller 1m reflect the difference between actual values of plant parameters and initial values included in plant model. The main problem is to establish the best correspondence between parameter and measured output.

3 Lab Experiment of power plant

3.1 Structure for diagnosis operations

This methodology of fault detection and isolation we intend to apply in the control system of hydro power plant.

We consider a hydropower plant structure designed in figure 5, (a pumped storage plant), which uses a combination of pumped water and natural stream flow to produce energy. This is a better solution for our hydro power plant, which operates on a daily/ weekly cycle. It is easy to adapt an actual storage plant to work as pumped-storage plant. These plants convert relatively low cost off-peak thermal generation from nuclear or coal - fired plants into high value peak power.

The concept of pumped - storage hydro was analysed in a lot of papers or projects, the major topics in each paper converted the following aspects:

- characteristics and procedures for evaluation of daily / weekly cycle for pumped storage plants.
- economic analysis of daily/weekly cycle for pumped - storage plants.

3.2 Laboratory experiments

In this paper, we focus on the level control system for the upper and lower reservoirs and the pump control, using laboratory equipment. Also, it is necessary to develop a fault detection architecture based on real time information from level and pressure transducers.

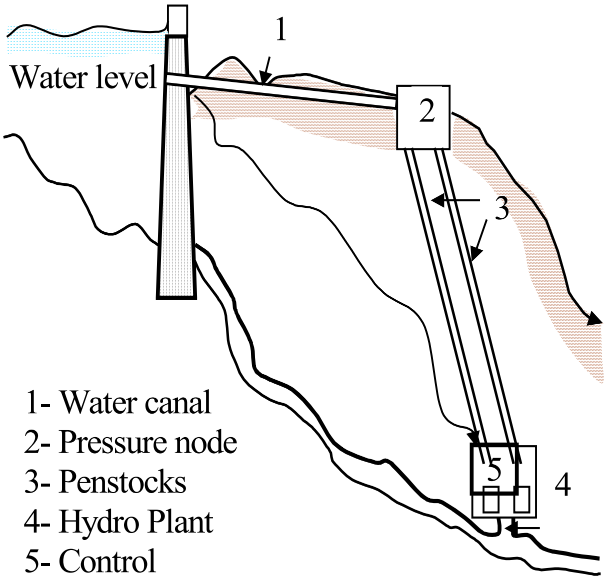


Fig. 6. Hydro power plant structure

Usual, the control system assures the constant level in the upper reservoir via control valves of turbine water admission. For this structure we consider the following possible additive faults:

- the plant model input (water flow to turbine) is function of controller output and actuator fault:

$$U_{pl} = (K_E + K_D).\, X_C \qquad (12)$$

where K_D is additive actuator fault.

- the pipeline leaks;
- the level sensor fault.

The FDI structure from the figure 4 will be developed for hydro power plant including the possible faults (see figure 6).

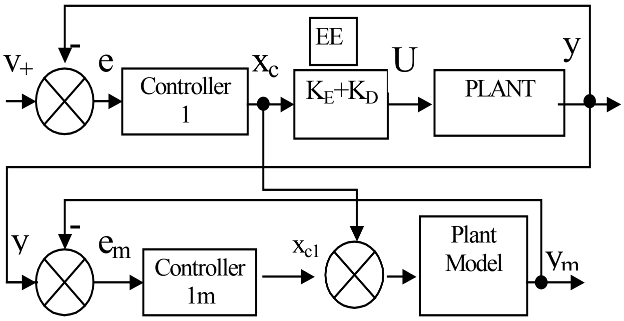


Fig.6. FDI Actuator Structure

The mathematical model of control system has the form:

$$L(s) = \frac{K}{1+T_l s} F_r(s) - \frac{K}{1+T_l s} F_1(s) + \Delta L_T(s)$$

$$F_1(s) = \frac{K_C}{1+Tps} x_C(s) + \frac{K_1}{1+T_p s} U_T(s) + \frac{K_D}{1+T_p s} X_C(s)$$

$$X_c(s) = -K_c(1 + K_I / s).L(s) \qquad (13)$$

where $X_c(s)$ is controller output, $\Delta L_T(s)$ is the transducer fault and K_D represent the actuator fault.

It is difficult to verify the fault detection algorithm on the real hydro plant because there appears a lot of Security and technological problems. In this case we use the physical Simulator platform from the industrial Process Control laboratory. This hydraulic Platform has the same structure with the diagram of a hydro power plant.

The basic components of the experimental platform are as follows: two reservoirs, electric pump, control valves, plastic tubes with elbows, and sensors for level and flow measurement, electrical components, mechanical components. The kit allows level and flow control and contains individual modules that can be combined in different configurations, using the Matlab Simulink software and Quanser WinCon 5.1 interface for Level control via pump voltage command. On the platform we may realise different types of faults: level sensor faults, pump voltage, pipe leaks etc.

The structure of the FDI and control system structure is presented in figure 7, where the Two tank Lab equipment and Power interface are equivalent with the process level and control system ad FDI software represent the upper control level organised in the holon structure corresponding to figure 3.

The hydraulic diagram is presented in figure 8.

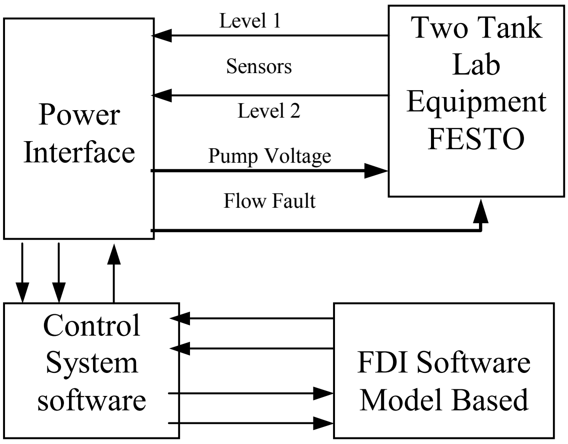


Figure 7. Experimental control structure

The experimental platform has the same structure with the pumped - storage structure and we have developed the following experiments:

-The Mathematical Model of the lab Process:

$$A_1\frac{dL_1}{dt}=-CX_S\sqrt{L_1-L_2+b}+F_P(U,H)-Q_f\left(L_1-L_2\right) \quad (14)$$

$$A_2\frac{dL_2}{dt}=CX_S\sqrt{L_1-L_2+b}-F_P(U,H)+ +Q_f\left(L_1-L_2\right) \quad (15)$$

where and are the water levels in upper and lower reservoir, *Fp* - sum flow of pumps, *Qf* -frictions loss in pipes and *Xs* is equivalent with control valve signal, and *H*- the pump head.

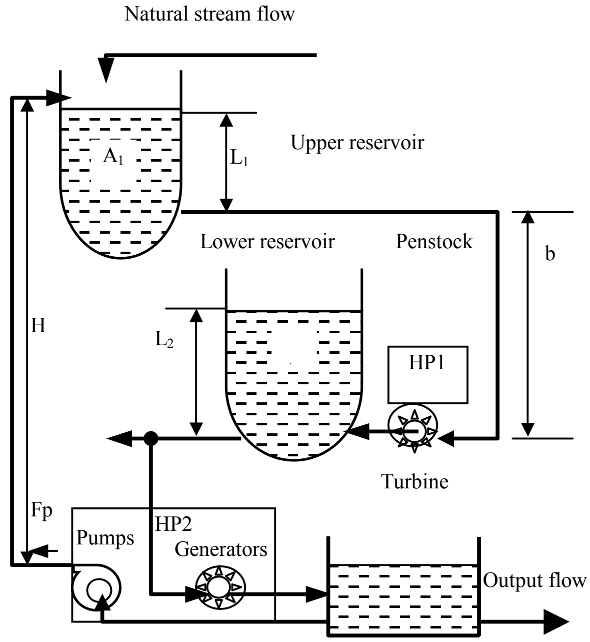
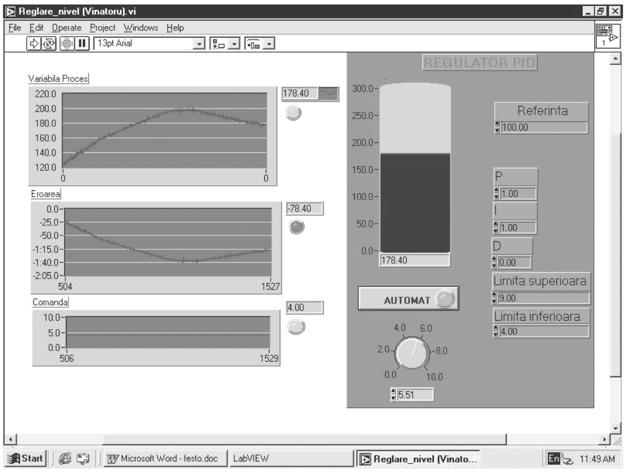


Fig. 8. Lab platform hydraulic diagram

3.3 Computer programs - steady operation

LabView CONTROL Software Widow, see Fig. 9, gives information on level control of the unit in operation. Any measured on-line data, site test data, and model tests could be put on the screen. The best operating point of the unit is determined by profit in function of power characteristic and on-line measured data. By following instructions, the profit could be increased obtaining the best results.

Any of applications and charts could be analysed on-line, or saved in files for later investigation. The saved data could be very important in the case of incidents and accidents.



Reglare_nivel (Vinatoru).vi

Variabila Proces 178.40

Eroarea -78.40

Comanda 4.00

178.40

Referinta 100.00

P 1.00

I 1.00

D 0.00

Limita superioara 9.00

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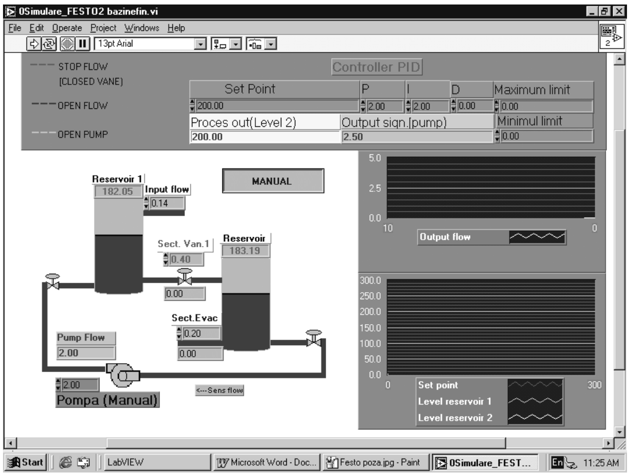
5.51

Fig. 9. Level control screen

For pumped storage hydropower system we develop another screen, see figure 10, where the operator can see the reservoirs level variations in real time and the status of hydro circuit elements.



Set Point: 200.00
P: 2.00
I: 2.00
D: 0.00
Maximum limit: 0.00
Proces out(Level 2): 200.00
Output sign.[pump]: 2.50
Minimul limit: 0.00
Reservoir 1: 182.05
Input flow: 0.14
Sect. Van.1: 0.40
0.00
Reservoir: 183.19
Sect.Evac: 0.20
0.00
Pump Flow: 2.00
2.00

Fig. 10 The pumped storage screen

3.4 The Mathematical Model of the Experimental Process

The experimental platform has the same structure with the pumped - storage structure (see figure 1). In the mathematical model we use the same notations of process parameters. The experimental platform is fully described by the equations (5) and (6). The platform characteristics: $A_1 = A_2 = 4*10^{-3}$ m^2, b = 0.2 m, CS = 2.11 (experimental result), $L_{10} = 0.24$ m, $L_{20} = 0.21$ m.

Substituting in (14) and (15) the numerical values of physical parameters of the platform, the model is represented by (16) and (17).

$$4\frac{dL_1}{dt} = -2{,}11 X_S\sqrt{L_1 - L_2 + 2} + F_P(u, L_2) + Nf \qquad (16)$$

$$4\frac{dL_2}{dt} = 2{,}11 X_S\sqrt{L_1 - L_2 + 2} - F_P(u, L_2) - Of \qquad (17)$$

where X_S is the value of control signal ($X_S = 0$, if $L_1 \le 0{,}1$), Nf is the natural flow rate, Of is the output flow rate and $F_P(U)$ is the pump flow:

$$F_P(U) = \begin{cases} kU & for \quad L_2 > 0 \\ 0 & for \quad L_2 = 0 \end{cases} \qquad (18)$$

were k = 1.5 *10^{-3} m^3/s/V.

3.5 The Experimental Results

a) Level control

The experiments simulate some of real situations from pumped - storage hydro plants.

- First experiment put in evidence limits of level variations in upper and lower reservoir, and we implemented the level control in the lower reservoir and imposed the output flow (*Of*) of HP2 as a function of power grid demand, which was considered as a sinus function, $O_f = 0.6 + 0{,}7\sin(0{,}2\pi t)$. The variations of upper and lower reservoir levels are presented in figure 11.

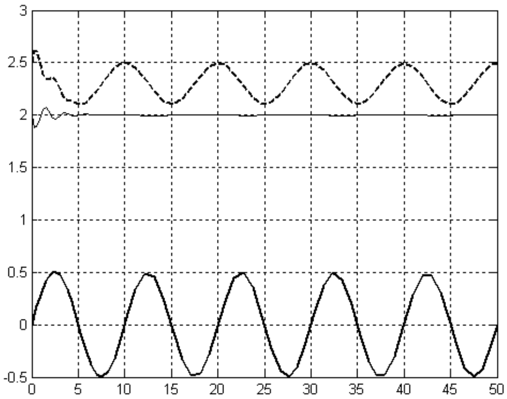


Fig. 11 Level control in lower reservoir HP2 flow is DF=0.5+0.5.sin 0.2*w*t

In figure 12 are presented the same variations with the square signal command of the output flow (*Of*) of HP2 (amplitude of discharge).

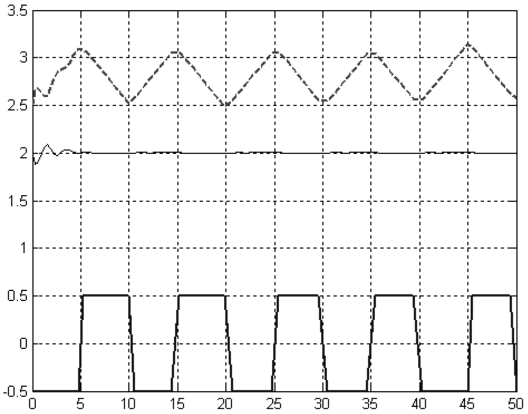


Fig. 12 Level control in lower reservoir HP2 with square signal flow

In figure 13 are presented the same variations with the $Of = 0{,}8 + 0.7\sin(0{,}2\pi t)$ (we increase the amplitude of discharge).In this case, the hydro system is unstable and after 40 hours, the upper reservoir will be empty and the lower reservoir will be full with the oscillations of levels:

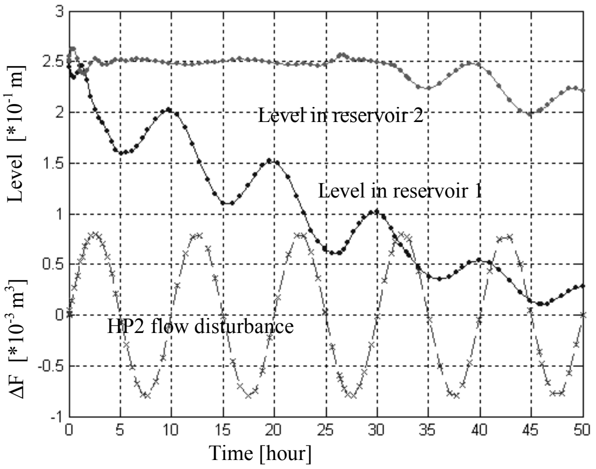


Fig. 13. Level control in lower reservoir, HP2 flow is $DF=0.8+0.7.\sin 0.2\pi\tau$

According with graphs presented in figures 5 and 6, level oscillations will occur, having an amplitude of 20% in the upper reservoir and 5% in the lower reservoir.

Safe operation conditions require that the level in the upper reservoir to be no less than 20% from nominal level and the flow through HP2 can be modified between the following limits: ± 20% in ratio with natural river flow [4].

b) Experimental Implementation of FDI Structure

For the lab equipment we implemented the FDI structure presented in figure 7, were:

- Quanser power interface realise the connexions between two-tank lab equipment and WinCon software, via data acquisition card installed from PC computer. This interface realise the compatibility between digital signals used in WinCon programs and analogue data of pressure sensors and to control voltage of the pump situated on the two-tank equipment;
- The lab experiment offers the possibility to create the control system software and the FDI structure (corresponding with structure presented in figure 6) using Matlab-Simulink and the RTW WinCon transforms this program in WinCon source C++.

The results of level control in tank 1 and tank 2 are presented in figure 14.

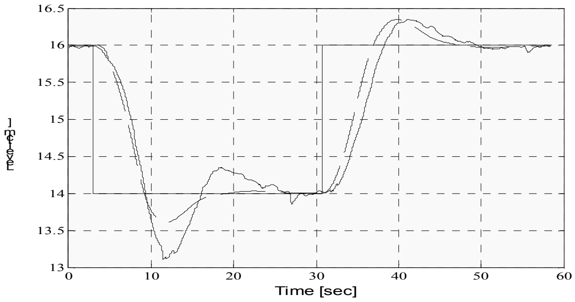


Fig. 14. Step response of L1 level control system.

In the experiment we are modified the section Ao1 in the lab platform in report with the initial value included in the plant model of the FDI structure. The FDI structure detects the difference between the actual value of A_{01} and the model value. This aspect is presented in figure 15 were the output xc1 of the controller 1m is zero in normal conditions and beginning with t=50 sec., (the fault period) the output xc1 $\neq$ 0, and her value is proportional with the difference: A01 model – A01 actual.

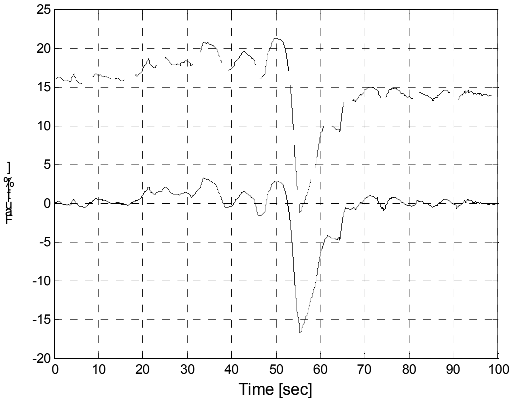


Fig. 15 Fault detection system response

4 Conclusion

The paper established a methodology to use the results from a simulation on a laboratory installation to control and fault detection for the hydro power plants:

- Fault detection and identification using dedicated observer's algorithms (FDI) with the structure presented in figure 7.
- The level control with optimal perturbation response and FDI response (see figure 15).

The research will be extended to also implement modelling algorithms for the mechanical and electrical part of the hydroelectric groups.

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