Real Time Adaptive Fuzzy Control of Coupled Levels via Programmable Logic Controller

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ABSTRACT

The coupled levels control is important for the energy and material balance in many industrial installations. The multivariable, nonlinear and ill-defined when the inflow and the outflow are supplied via pumps plant is difficult to model and controlby classical means. Intelligent approaches based on fuzzy logic (FL) and genetic algorithms (GAs) offer a proper alternative but the control algorithms are sophisticated for real time application. This paper suggests a methodology for the implementation of complex FL controllers (FLCs) on programmable logic controllers (PLC). First a model-free two-variable MamdaniFLC is designed and the data from real time control used for Takagi-Sugeno-Kang FL modelling of the nonlinear plant and its validation. Then a second level two-variable FL supervisor is added for improving system performance via auto-tuning of the scaling factors of the main FLC. The adaptive supervisor based FLC is approximated to a TSK-based parallel distributed compensator (PDC) with simple structure of linear controllers in each linearization zone and fuzzy estimation of the matching of the current system state to the defined zones. The PDC is validated and programmed in an industrial PLC for real time coupled levels control. This methodologyis applied to design a secondsophisticated PDC with two-variable decoupling controllers in the local linear systems. The real time control with the two PDCs via PLC and in MATLAB^{TM} shows closesystems performancesand reduced overshoot and settling time in the adaptive PDC system.

Keywords
Fuzzy logic control, genetic algorithms, parallel distributed compensation, programmable logic controller, real time, coupled levels, supervisor based adaptation, Takagi-Sugeno-Kang modelling.

1. INTRODUCTION

Level control is important in most industrial processes in waste water treatment, power energy, biotechnology, oil refining, chemical industry, etc. for providing energy and materials balance [1-5]. However, often it is difficult to ensure by classical means since besides nonlinearthe plant is also ill-defined, when pumps provide inflow and outflow of liquid to tanks, and multivariable for two or more coupled levels. A plant model necessary for the classic controllers design cannot be derived analytically or via identification. Then intelligent approaches based on fuzzy logic (FL) and genetic algorithms (GAs) are successfully applied to ensure closed loop system stability by a model-free design of nonlinear multivariable controllers [4-6]. A single level fuzzy control is developed in [7-11]where the plant is nonlinear but with self-regulation. A more advanced intelligent technique is suggested for the coupled level fuzzy control in [12, 13]. In order to improve the system performance at changesof plant and operation conditions different tuning optimization and adaptation mechanisms are considered [12-19], based on the classical adaptive control theory [20], GAs [10, 11, 21-24] or second control level fuzzy logic supervisors (FLSs) [5, 25, 26]. Subjected to adjustment or optimization are the scaling factors (ScFs), the membership functions (MFs)(usually the peaks or the singletons)and the rule bases mainly bychanging the consequents (singletons) or the rule-base relation matrix. The adaptation of the ScFs causes a uniform change of the FL controller (FLC) sensitivity, resolution, gains, MFs universes of discourse while the MFs adaptation results in modification of the FLC gain in a specific area of the universe of discourse. Though there exists a software to support the FLC design, optimization, adaptation and simulation [27-29], the real time industrial applications are only few. The reason is the computation complexity of the design and the algorithm. In [30] a programmable logic controller (PLC) implementation is developed for a simple FLC that complies with the real time control restrictions for fast response and limited resources. In [25, 26] a procedure for the design and the PLC completion of an adaptive FLS-based fuzzy controller (ASFLC)is suggested for multivariable and ill-conditioned plants. The idea is to approximate and validate the designed ASFLC by a parallel distributed compensation (PDC) using GAs with data from the real time plant adaptive FLC-FLS control. The PDC consists of Sugeno models and standard local linear controllers which makes it suitable for programming and running on industrial PLCs.

The aim of the present paper is to implement a two-variable PDC in a PLC and to apply for the PLC real time control of coupled levels in a laboratory two-tank system. The PLC used is SIEMENS SIMATIC S7313. Experimental investigations of the two-variable PDC closed loop system real time control by the PLC and in MATLAB™ are carried out. Two types of PDC - $PDC_1$and PDC_2, identical in structures and both designed on the basis of a derived TSK plant model are tested. The parameters of PDC_1 are computed as a result of approximation of a designed ASFLC. The parameters of PDC_2 are derived to ensure stability anddecouplingin the local linear two-variable closed loop systems.

The rest of the paper is organized as follows. In Section 2 the two approaches to the design of PDC for the two-variable control of the coupled levels are briefly presented- the ASFLC design and its approximation to PDC_1 from [26] and the design of PDC_2 with local linear decoupling controllers from [21]. In Section 3 the PLC completion of the two-variable PDCis illustrated. The results from the real time control via PLC and via MATLAB™ are described and discussed in Section 4. Section 5 is devoted to conclusions and prospects for future research.

2. DESIGN OF PARALLEL DISTRIBUTED COMPENSATION FOR LEVELS

The plant and the controller are shown in Fig.1. The plant consists of a twotanks connected via apipe at bottoms. Two industrial pressure difference level transducers measure the tanks levels and two DC pumps ensure liquid inflow (Pump 1) and liquid outflow (Pump 2). The levels H_i, i=1,2, are controlled to maintain desired references H_{ir} by changing the voltage to the pumps U_i. The ranges for the plant operation are $H_1 \in [0,60]$ cm, $H_2 \in [0,30]$ cm and $U_i \in [0,10]$ V. The controller - an industrial PLC-SIEMENS SIMATIC S7 313 or a computer with Simulink model in MATLAB™and aplant-computer interface on the place of the PLC (not shown in Fig.1), performs real time fuzzy logic control.

The plant is nonlinear, ill-defined and two-variable and standard open loop identification is impossible – a step change of each plant input U_i results in overflow or dryingof tanks. Therefore first a model-free two-variable Mamdani incremental PI FLC with inputs the main channel e_i and the cross-channel e_j, $i \neq j$, errors and PI post-processing – $C_{PIi}(s)=K_{pi}(1+1/T_{Ii}s)$, is designed and applied for real time plant control. The data collected is used for derivation and validation of a nonlinear two-variable plant model. The Takagi-Sugeno-Kang (TSK) modelling technique combined with the GAs parameter optimization can map any plant nonlinearityon the basis of simple linear models thus facilitating the nonlinear two-variable controller design and improving the control algorithm to better respond to the plant nonlinearity.

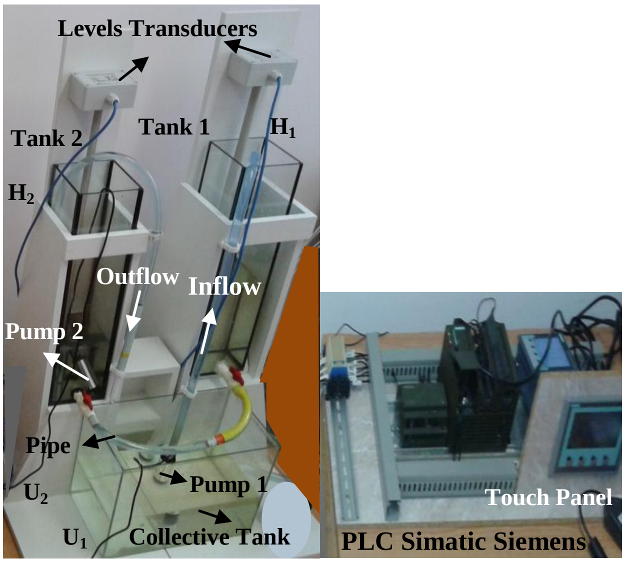

Fig.1. Two-variable plant and programmable logic controller for the fuzzy coupled levels control

Here the two-variable TSK plant model, shown in Fig.2, is built of two Sugeno models for defining the overlapping linearization zones for the two levels y_i,=H_i, and transfer matrices models of the dynamic properties of the plant in each k-th zone, k =1,2,3:

$$\mathbf{P}^{k}(s) = \begin{bmatrix} P_{11}^{k}(s) & P_{12}^{k}(s) \\ P_{21}^{k}(s) & P_{22}^{k}(s) \end{bmatrix}.$$

The Sugeno models are expert defined and the transfer matrix parameters $\mathbf{q}_{TSK}$are computed in GAs minimization of the fitness function:

$$\mathbf{F}_{TSK} = \int \sum_{i=1}^{2} \{[H_{iTSK}(t) - H_{iex}(t)]/H_{iex}(t)\}^2 dt \rightarrow \underbrace{\mathbf{min}}_{\mathbf{q}_{TSK}}, \quad (1)$$

Where theTSK plant modelinputs are u_i=$U_{ex}$and y_i=H_{iex}in Fig.2.The data (U_{iex},H_{iex}) are recorded during the real time control of the laboratory-scale plant with the designed two-variable MamdaniPI-FLC. It is divided into apart used in (1) for the TSK modelling, and a part (1/3 of all data) for model validation. In order to successfully mapthe plant nonlinearitythe data (U_{iex},H_{iex}) provided have to be rich in magnitudes and frequencies and to cover the operation range of the plant. Therefore,the closed loop FLC system is subjected to a variety of reference changes. These data are pre-processed byfiltering of noise and correlated data, thus reducing the sample in size.

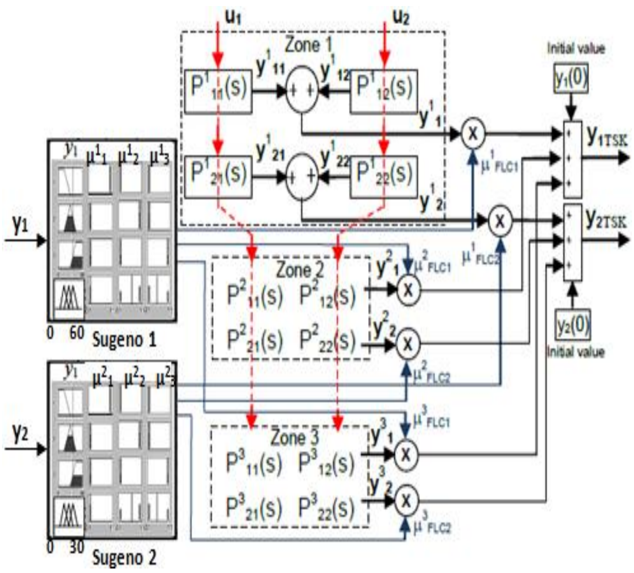

Fig.2. Two-variable TSK plant model for 3 linearization zones

The optimal plant Ziegler-Nichols transfer functions of the local two-variable plants in each zone are presented in Table 1.Then two types of two-variable nonlinear fuzzy controllers are designed on the basis of the TSK plant model.

Adaptive Supervisor based FLC

It consists of the empirically designed main PI Mamdani FLC and a second level FLS for on-line auto-tuning of the ScFsK_e, $K_{\Delta e}$, K_p, T_I, etc. of the main FLC in order to keep selected performance indicators **Π** within the defined norm term at changesof plant or operation conditions. The block diagram of an ASFLC is shown in Fig.3. The designed ASFLC uses the current estimates for the over/undershoot y_i/y_{ri} of each level to fuzzy adjust the scaling factor for the cross-channel error and the rate of control u_i for auto-tuning of the proportional gains of the PI post-processing. It leads to improvement in real plant control of the process performance indicators of the FLC system by reduction of coupling, overshoot and settling time.

To reduce the structure and computation complexity the ASFLC is approximated to a simple PDC similar to the

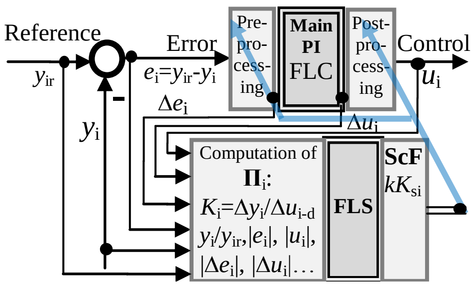

Fig.3. Block diagram of a ASFLC

Table 1.Transfer functions of the TSK local plants

Zone	$P_{11}(s)$	$P_{12}(s)$	$P_{21}(s)$	$P_{22}(s)$
1	$\frac{1e^{-5.4s}}{10s+1}$	$\frac{-0.85e^{-0.95s}}{40s+1}$	$\frac{0.15e^{-0.5s}}{10s+1}$	$\frac{-0.33e^{-40s}}{(48s+1)}$
2	$\frac{3.6e^{-4.6s}}{(10s+1)}$	$\frac{-0.18e^{-1.86s}}{(40s+1)}$	$\frac{0.6e^{-0.98s}}{(10s+1)}$	$\frac{-0.6e^{-5.2s}}{(40s+1)}$
3	$\frac{6e^{-6.3s}}{(10s+1)}$	$\frac{-0.08e^{-0.95s}}{(40s+1)}$	$\frac{1.7e^{-10s}}{(14.1s+1)}$	$\frac{-0.18e^{-1.3s}}{(40s+1)}$

TSK plant model in Fig.2 structure and with identical Sugeno models. The local two-variable controllers inthe linearization zones are accepted to perform PI algorithm in the main and cross-channels. Their parameters $\mathbf{q}_{PDC}$ are computed in GAs minimization of the approximation error on the basis of experimental data for the control action $U_{iASFLCex}$from real time control and the fitness function:

$$\mathbf{F}_{PDC} = \int \sum_{i=1}^{2} \frac{[U_{iPDC}(t) - U_{iASFLC\ ex}(t)]^2}{U_{iASFLCex}(t)^2} dt \to \underbrace{\mathbf{min}}_{\mathbf{q}_{PDC}}. \quad (2)$$

Decoupling Parallel Distributed Compensation

It consists of the TSK Sugeno models that determine the linearization zones for each level and two-variable linear PI controllers for each zone designed on the principle of decoupling of the local linear systems. The block diagram is similar to the TSK plant in Fig.2 where the local plant transfer matrices in each linearization zone are substituted by transfer matrices of the local decoupling controllers:

$$\mathbf{C}^k(s) = \begin{bmatrix} C_{11}^k(s) & C_{12}^k(s) \\ C_{21}^k(s) & C_{22}^k(s) \end{bmatrix}.$$

The main channel controllers are selected to be linear PI $C_{ii}(s) = K_{pii}\left(1 + \frac{1}{T_{Iii}\,s}\right)$. The cross-controllers are computed from $C_{ji}^k(s) = -\frac{P_{ji}^k(s)C_{ii}(s)}{P_{jj}^k(s)}$to ensure decoupling in the local two-variable systems and then are approximated to PI linear controllers. As a result of the decouplingthe tuning of the main controllers accounts for equivalent plants $P_{eqii}^k(s) = P_{ii}^k(s)\left[1 - \frac{P_{12}^k(s)P_{21}^k(s)}{P_{11}^k(s)P_{22}^k(s)}\right]$approximated to Ziegler-Nichols models$P_{eqii}^k(s) \approx \frac{K_{eqii}\,e^{-\tau_{eqii}\,s}}{T_{eqii}\,s+1}$ [1] . The computation of the controllers gains K_{pii} and integral action times$T_{Iii}$is based on an engineering approach [1-5]for ensuring minimal overshoot σ and settling time t_s in the decoupled local linear closed loop systems with theequivalent plants: K_{pii}=A.T_{eqii}/(K_{eqii}.τ_{eqii}); $T_{i\ ii}$=B.T_{eqii}, K_{Iii}= $K_{pii}/T_{i\ ii}$ (A=0.1÷1; B=0.1÷2).

Thus the two developed PDCs are identical in structure with different parameters of the local PI controllers, presented in Table 2.

Table 2.PDC local PI controllers' parameters

	Zone	PDC typefrom ASFLC approximation	PDC typefrom Local Decoupling
$C_{11}(s)$ (K_{p11}, T_{i11})	1	(0.58, 24.5)	(1, 18)
	2	(0.75, 75.5)	(0.19, 9)
	3	(0.92, 95)	(0.08, 8.1)
$C_{12}(s)$ (K_{p12}, T_{i12})	1	(-0.0014, 7)	(-0.37, 13)
	2	(-0.006, 30)	(-0.05, 8.9)
	3	(-0.12, 115)	(-0.25, 2.7)
$C_{21}(s)$ (K_{p21}, T_{i2})	1	(0.0031, 3.9)	(2.2, 85)
	2	(0.47, 30.5)	(0.9, 43)
	3	(0.39, 20)	(2.2, 23)
$C_{22}(s)$ (K_{p22}, T_{i22})	1	(-0.017, 1.27)	(-1.44, 3.2)
	2	(-1.8, 132)	(-4.1, 36)
	3	(-0.35, 32. 4)	(-56.2, 34.2)

3. PLC COMPLETION OF PARALLEL DISTRIBUTED COMPENSATIONS

The programming of the PLC to perform real time control using the designed PDCs follows the steps bellow.

1. Programming of an organization block that includes functions for: initial conditions settling;safety end of control; automatic real time control; manual control; assignment and change of input data; recording of output data for levels, references, controls and parameters for future processing.
2. Programming of the two Sugeno models by the help of the Fuzzy Control application, developed by Siemens [29], which differ in the universes of discourse for the two levels and hence the parameters of the input MFs with the norm in the middle. The programming ends with producing of two fuzzy functional blocks, each provided with its data base block.
3. Programming of the PDC structure of Sugeno models and local PI controllers for real time control in automatic mode:
   - reading of the parameters and the references of the local PI controllers at the start of the real time control;
   - reading at each sample period of the current measured values for the two levels from the Analog-to-Digital Converter and scaling to convert them to levels;
   - passing of the current levels values to the Sugeno models to identify the degree $\mu^k_i$of matching to the defined three linearization zones;
   - passing of the current levels values to the local controllers for computation of the local control actions;
   - scaling of each local control action by the corresponding degree μkiof match to the linear operation zone defined;
   - mixing of scaled controls for computing the weighted average final channel controls Uij;
   - mixing of the main and the cross-channel controls for computing the PDC outputs Ui=Uii +Uij;
   - observation of controls bounds 0÷10V and switching off of the integrating component of the local PI controller at reaching these bounds (anti-wind up precautions);
   - keeping a record of levels, references and controls with a given sample time needed for later playback and process history.
4. Programming of the functions in manual mode
   - start function - settling of initial conditions for equal small references for the two levels and initial zero controls of all local controllers by forcing Pump 1 for filling the two tanks or forcing Pump 2 for empting the two tanks to reach equal levels, equal to a desired small level;
   - end function – making zero all local controllers' outputs;
   - assignment of input data - sampling periods for control and for data recording, references for the two levels and their changes in time, parameters of the local controllers;
   - switching between modes manual-automatic-programming;
   - start and interruption of the automatic mode.
5. Programming of a SCADA system including mnemonics of the process, input-output operator-PLC communications – input data, output numerical and graphical information about the system operation using WINCC and the facilities of the operator Touch Panel.

4. PLC AND MATLAB™PARALLEL DISTRIBUTED COMPENSATION REAL TIME CONTROL OF COUPLED LEVELS

The experimental investigation of the PDC control of the coupled levels in a two-tank laboratory system is carried out using PLC and MATLAB™ real time with parameters ofthe designed two types of PDC. The step responses of the following systems are compared:

- System 1 – with ASFLC based PDC, completed on PLC, with step responses in Fig.4;
- System 2 – with PDC with decoupling local PIcontrollers, completed on PLC, with step responses in Fig.5;
- System 3 – with ASFLC based PDC, completed in aSimulink model of MATLAB™ real time, with stepresponses in Fig.6;
- System 4 – with PDC with decoupling local PI controllers, completed in a Simulink model of MATLAB™ real time,with step responses in Fig.7.

Different step references are applied in order to assess the effect of plant nonlinearity (different plant model parameters) and the channels coupling on the systems performance when operating in different operation points. The main performance indicators considered are:

Absolute

- maximal dynamic deviation from reference H_{im},cm;
- settling time t_{si}, s.

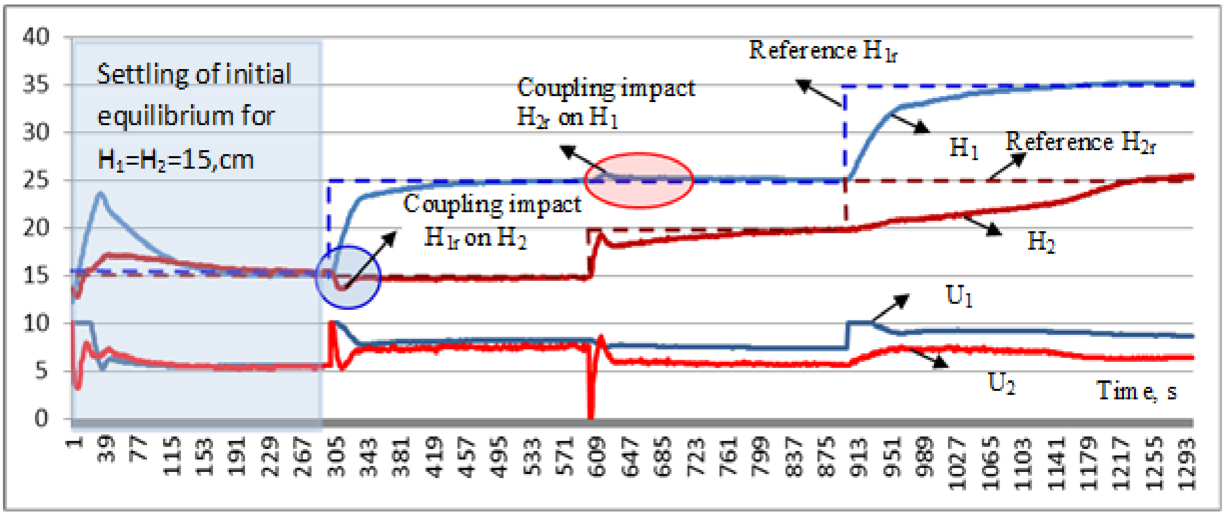

Fig. 4.Step responses of levels and control actions from adaptive PDC-PLC real time control in System 1

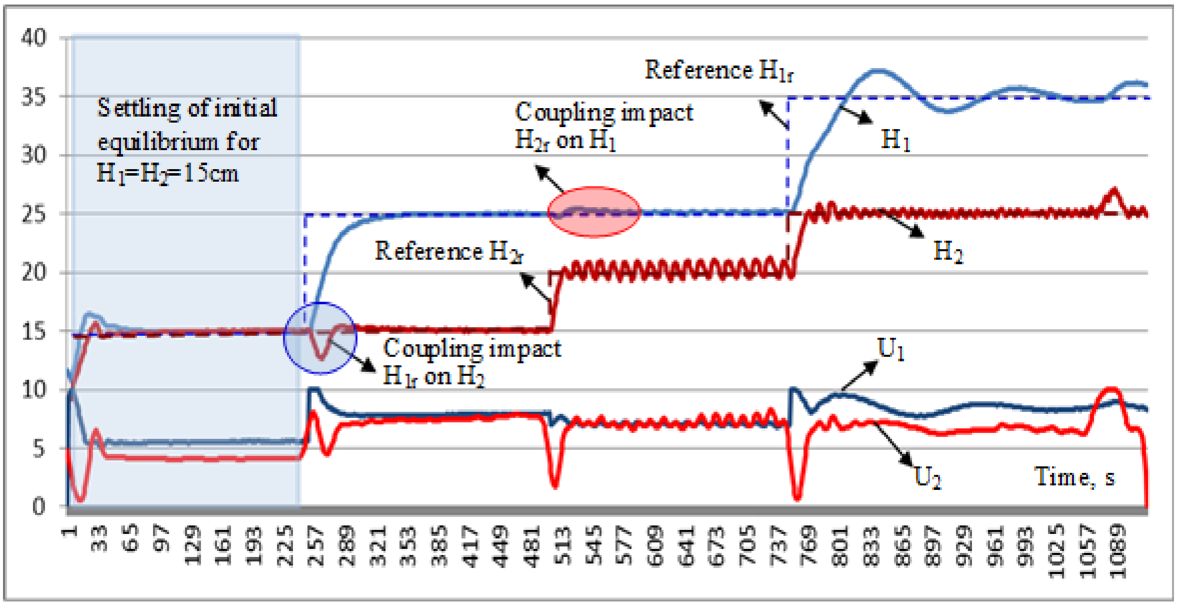

Fig. 5.Step responses of levels and control actions from decoupling PDC-PLC real time control in System 2

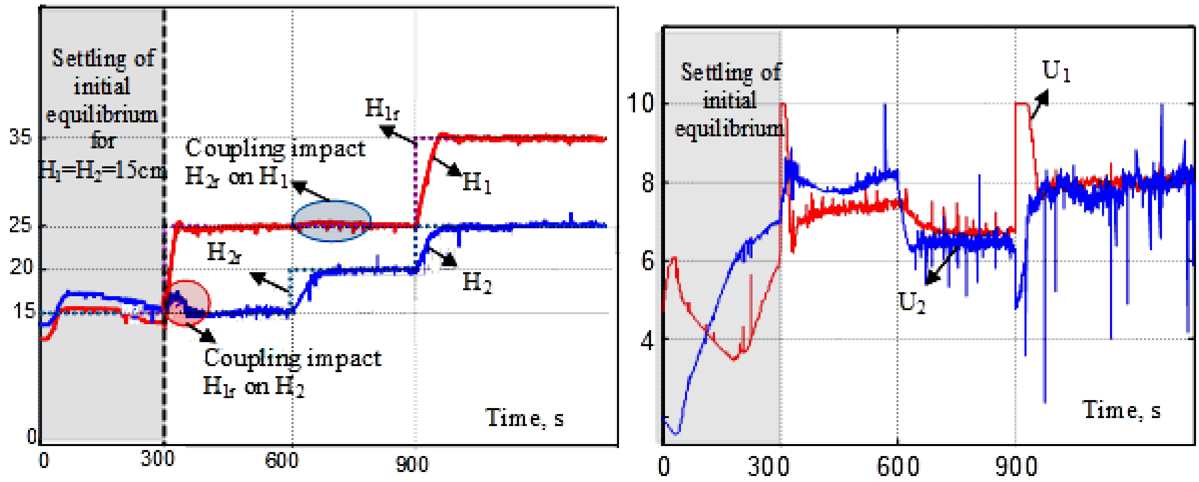

Fig. 6.Step responses of levels and controls from adaptive PDC-MATLAB™ real time control in System 3

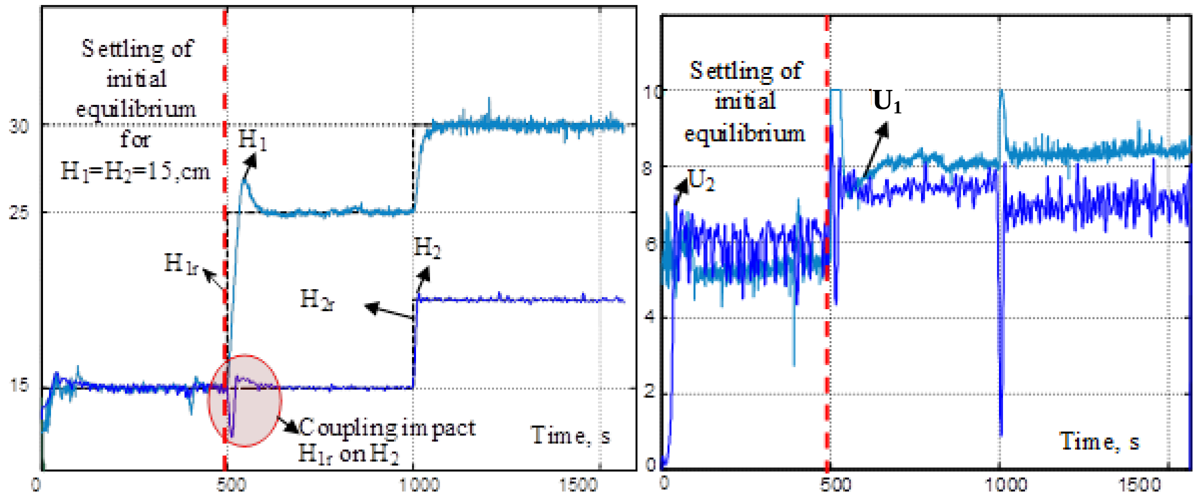

Fig. 7.Step responses of levels and controls from decoupling PDC-MATLAB™ real time control in System 4

Relative (dimensionless)

- overshoot σ_i, defined for the level which reference has been changed by $\sigma_i= H_{im}/\Delta H_{ir}$, and for the cross-channel level that is affected by this change of the reference while its own reference stays unchanged by$\sigma_j=|H_{jm}|/\Delta H_{ir},\Delta H_{jr}=0, i\neq j$;

- mean value of the control action U_{1av}/U_{2av}, V as an estimate for the mean energy consumption for control;

-accepted energy-efficiency indicator EEF=EEF$_1$+EEF$_2$, where$\text{EEF}_i=\frac{\int_{t_o}^{t_f} U_i\,dt-U_{oi}}{T_m\sum\Delta H_{ir}}$ is the accumulated control action for a given plant output per total time of observation (experiments) $T_m=t_f-t_o$ and total reference change for the period. The first step response is related to establishing of equilibrium initial conditions and is not considered in the system performance evaluation. It ends at time t_o with final value of the accumulated control U_{oi}. The greater EEF the less economic the control is.

The assessed performance indicators are shown in Table 3, where the coupling estimates are emphasized in bold. The analysis of the results shows that the processes from real time control via PLC (the real world system) and in MATLAB™ (theoretical) have close values for the performance indicators. The adaptive PDC system has a reduced or no overshoot and in most cases faster step responses and reduced coupling effect in magnitude and duration. The adaptive and the decoupling PDC systems are equivalent with respect to the EEF indicator, which showsthe smaller the EEF indicator value - the lower the energy consumption for control by the pumps. The MATLAB™ real time control is more economic than the PLC control. The step responses of the PLC system with the decoupling PDC have oscillations in steady state at higher references probably due to increased measurement noise sensitivity.

The PDC is easily programmed on industrial PLCs for real time control which can facilitate the wide engineering application of the more sophisticated adaptive or decoupling FL model-free control of various processes.

5. CONCLUSION AND FUTURE RESEARCH

The main results of the present investigation are the following.

A PLC completion of designed two types of two-variable parallel distributed compensations for the real time control of coupled levels in a laboratory two-tank system is presented. The plant is ill-defined, nonlinear and two-variable and requires intelligentapproaches to be modelled and controlled. The PDC may be result of approximation of a more sophisticated fuzzy logic controller such as a multivariable adaptive supervised FLC, built of many fuzzy logic blocks, or it can be designed to ensure decoupling in the local multivariable system. The PDC design is bounded to the TSK plant modelling which is generally based on experimental data, provided by a designed model-free FLC real time control. A TSK model can represent any nonlinear plant. A PDC exists for any TSK model. This confirms the possibility that any FLC can be approximated to a PDC which can be implemented in a PLC for real time operation and wide area of industrial applications.

Experiments from real time PLC and MATLAB™ coupled levels control in close to industrial environment are performed to prove that the industrial and the theoretical implementation of the PDC principle results in processes with equally good performance. The industrial PLCs facilitate the fuzzy control of complex processes which cannot be satisfactory modelled and hence controlled by classical means.

The future research will focus on implementation of the PDC-PLC real time control of industrial plants from power energy.

Table 3. Performance indicators of the investigated systems in real time control

		PDC system			
		Adaptive		**Decoupling**	
Reference step Response	**Performance indicators**	**PLC Fig.4**	**MATLAB™ Fig.6**	**PLC Fig.5**	**MATLAB™ Fig.7**
$\Delta H_{1з}$=15÷25, cm $H_{2з}$=15, cm	H_{1m} / H_{2m}, cm	0/**-1.8**	0.5/**2**	0/**-2**	2/**-2.5**
	σ_1 / σ_2, %	0/**18**	5/**20**	0/**20**	20/**25**
	t_{p1} / t_{p2}, s	150/**50**	80/**90**	80/**50**	100/**100**
	U_{1av}/U_{2av}, V	7/**8**	7.5/**8**	7.5/**7.8**	8/**7.5**
$H_{1з}$=25, cm $\Delta H_{2з}$=15÷20, cm	H_{1m} / H_{2m}, cm	**0.5**/0	**0.05**/0	**0.5**/0	-
	σ_1 / σ_2, %	**5**/0	**0.5**/0	**5**/0	-
	t_{p1} / t_{p2}, s	**20**/200	**10**/120	**30**/20	-
	U_{1av}/U_{2av}, V	**5.5**/7.4	**6.8**/6.5	**6.5**/6.5	-
ΔH_{1r}=25÷35, cm $\Delta H_{2з}$=20÷25, cm	H_{1m} / H_{2m}, cm	0/0	0.5/0	2.5/0.5	-
	σ_1 / σ_2, %	0/0	5/5	25/10	-
	t_{p1} / t_{p2}, s	150/300	80/90	350/500	-
	U_{1av}/U_{2av}, V	7/8.7	8/8	7.5/8.7	-
$\Delta H_{1з}$=25÷30, cm $\Delta H_{2з}$=15÷20, cm	H_{1m} / H_{2m}, cm	-	-	0/0	0/0.5
	σ_1 / σ_2, %	-	-	0/0	0/10
	t_{p1} / t_{p2}, s	-	-	100/70	50/30
	U_{1av}/U_{2av}, V	-	-	7.8/8	8.4/7
Energy efficiency	EEF, V/(s.cm)	1.15	0.79	1.13	1.88

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