Control Engineering Practice 71 (2018) 53–60

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Parallel distributed compensation for improvement of level control in carbonization column for soda production

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A R T I C L E I N F O

Keywords:
Carbonization column
Level control
Parallel distributed compensation
Takagi–Sugeno–Kang plant modelling

A B S T R A C T

The liquid level control is essential in many production installations but the classic approaches often fail to ensure the desired performance. The reasons are the plant nonlinearity, the level oscillations and the plant model uncertainties. The aim of the present investigation is to improve the existing linear control of the level in the carbonization columns for soda ash production by employing fuzzy logic using parallel distributed compensation (PDC). The design of the PDC is based on a nonlinear Takagi–Sugeno–Kang (TSK) plant model which is derived via genetic algorithms optimization and validated using the data from the real time linear level control. The PDC control performs soft blending of the outputs of several parallel local linear controllers each developed for the local linear plant of the TSK model. The fuzzy rules are represented by ordinary logics conditions to enable the PDC programming and use by an industrial programmable logic controller. The PDC increases the dynamic accuracy in the level control and reduces the frequency of the control oscillations compared to the previous linear control thus prolonging the lifetime of the expensive pneumatic actuators used.

1. Introduction

The control of liquid level is important for keeping material and energy balance in many installations such as wastewater treatment plants, boilers, evaporators, reactors, distillation columns, etc. (Jantzen, 2007; Neshkov, Yordanova, & Topalova, 2007; Stephanopoulos, 1984).

The carbonization column (CCl) is a key installation in the synthetic soda ash production. The carbonization process that takes place in a CCl is the most important in the soda ash plants and its performance determines the overall production quality. Therefore, its precise control is of great significance. The classic control techniques based on linear plant models often fail to meet the high demands for system performance. The basic reasons are the coupling among the variables, the plant nonlinearity and model uncertainty. Intelligent approaches using fuzzy logic (FL) and genetic algorithms (GAs) (Basil, Fernando, & Jiménez, 2003; Jantzen, 2007; Precup, David, Petriu, & Radac, 2013; Yordanova, 2014) can successfully improve the control of level by simple means (Ahmad, Ahmad, Redhu, & Gupta, 2012; Kanagasabai & Jaya, 2014; Kumar & Dhiman, 2011; Yordanova, 2015). Most of them are based on classic FL controllers (FLCs) with many rules, empirical or GAs based off-line tuning, analytical nonlinear plant models and simulations. In case of available plant input–output experimental data from plant linear control in real time a more precise nonlinear Takagi–Sugeno–Kang (TSK) plant model can be derived and used to develop a simple FLC with a few rules using parallel distributed compensation (PDC) (Tanaka & Wang, 2001; Yordanova, 2016; Yordanova & Sivchev, 2014) in order to improve the system performance. The PDC is tuned and the PDC system stability studied by applying the well-developed linear control theory methods. Besides, the PDC is simple which facilitates its programming in any programmable logic controller (PLC) for real time industrial implementations using ordinary logics rules for soft blending of the outputs of local linear controllers. Different applications for industrial processes in boilers, nuclear generators, etc. are reported for FL level control in Aydogmus (2015), Chabni, Taleb, Benbouali, and Bouthiba (2016), Mousa, Koutb, El-Araby, and Elsayed (2011), Shome and Ashok (2012) and Tan (2011), where real time experiments are carried out and expensive high-performance processors and software are substituted by low-cost FLC implementations on PLCs.

The aim of the present paper is to design and implement a PDC for the control of level in a carbonization column for the production of soda in order to improve the dynamic accuracy and reduce the control oscillations in the existing linear control system. The novelty concludes in the off-line transfer functions based nonlinear TSK plant

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https://doi.org/10.1016/j.conengprac.2017.10.003
Received 17 March 2017; Received in revised form 17 June 2017; Accepted 9 October 2017

Abbreviations

CCl	Carbonization column;
DCS	Distributed control system;
FL	Fuzzy logic;
GAs	Genetic algorithms;
MF	Membership function;
PDC	Parallel distributed compensation;
PI(D)	Proportional-plus-integral(-plus derivative) linear controller;
PLC	Programmable logic controller;
TSK	Takagi–Sugeno–Kang model;
ZN	Ziegler–Nichols model

modelling using GAs and data from the real time plant linear control, the design of a TSK based PDC and its completion on Honeywell PLCs of the plant Distributed Control System (DCS) (Experion overview, 2006). The improvements achieved are assessed from the real time PDC level control. The investigation is carried out by the help of MATLAB™ and its related Toolboxes (Fuzzy logic toolbox, 1998; MATLAB-Genetic algorithm, 2004).

The further organization of the paper is the following. Section 2 describes the plant — a carbonization process and the existing system for level control. In Section 3 a TSK plant model is derived. Section 4 presents the design of the FL-PDC. The PDC embedding in a Honeywell PLC, the system step responses from the real time PDC level control and the assessment of the system performance in comparison to the performance of the PI control system comprise Section 5. The conclusion and the future research are discussed in Section 6.

2. Level PI control in carbonization column

2.1. Carbonization process

Sodium bicarbonate ($\mathbf{NaHCO_3}$) suspension is produced in a carbonization column as a result of a chemical reaction known as carbonization of ammonia brine solution — a water ($\mathbf{H_2O}$) solution of salt (**NaCl**) and ammonia ($\mathbf{NH_3}$), when mixed with carbon dioxide CO_2 (Thieme, 2012):

$$\mathbf{NaCl + NH_3 + CO_2 + H_2O \rightleftarrows NaHCO_3 + NH_4CI\ (+energy)}.$$

The reaction is exothermic and reversible — no full transformation of the inputs to final products is achieved. The obtained $\mathbf{NaHCO_3}$ has the lowest solubility among all other chemical reagents. Therefore, the sufficiently high concentrations of **NaCl** and $\mathbf{NH_3}$ in the ammonia brine and of carbon dioxide $\mathbf{CO_2}$ in the mixed gas enables the most of the produced in the form of crystals $\mathbf{NaHCO_3}$ to be separated from the solution. The reaction is more complicated due to the crystals output and consists of many stages.

The liquid ammonia brine is inputted from the top of the column and flows down. In operation mode (with duration of 72 h) the CCl is fed also from its bottom by the "mixed gas"- a gas with high concentration of 80–85 vol. % $\mathbf{CO_2}$, and from the middle of the column by the "lean gas" with low concentration of 38–42 vol. % $\mathbf{CO_2}$. The "mixed" and the 'lean" gases go up in a counterflow to the liquid. The obtained sodium bicarbonate crystals suspension is let out of the CCl by the control valve at the bottom of the CCl while the unreacted gases go out through the top of the CCl. Since the reaction is exothermic the CCl consists of an upper absorption part and a lower cooling part — necessary for taking away the heat released. The crystals of $\mathbf{NaHCO_3}$ are accumulated on the cooling surfaces in the lower part of the column which worsens the heat exchange and hence deteriorates the performance of the CCl. In washing mode, which lasts 24 h, the CCl uses only a "lean" gas from the column bottom. Several CCls operate together for the production of the sodium bicarbonate suspension and the numbers of the columns in operation and in washing modes keep a constant ratio 3:1. The ammonia brine solution first feeds the "washing" columns and passes from the top to the bottom of the column in a counterflow to the lean gas thus cleaning the heat exchange surfaces taking the crystals of $\mathbf{NaHCO_3}$ off the cooling surfaces. This new liquid, known as a "precarbonated solution", is "washed" by the unreacted gas which goes up to the top to leave the column, and then feeds the columns in operation mode to perform the reaction. The usual flowrate of ammonia brine solution in a "washing column" is about 210–225 m^3/h and of a precarbonated solution — 60–75 m^3/h for each "operating column" again in ratio 3:1.

2.2. Existing system for linear control of the liquid level

The level control is crucial for the performance of the ammonia brine carbonization. The linear control system consists of a microwave radar level measuring transducer of a mounted on the top of the column transmitter (type VEGAPULS 52 K) and a radar antenna (rod antenna made by PTFE) inside the column. The transducer has an unified output of 4–20, mA and it is adjusted for measuring of level H in the range [0.5, 3], m (Radar product information, 1999).

The radar transducer's output is passed to the analog input of the DCS Honeywell Experion Process Knowledge System (Experion overview, 2006). The measured level is normalized in the DCS in the range [0, 100], % and indicated on the operator's screen. The existing proportional-plus-integral (PI) linear controller with transfer function $C(s) = K_p(1 + 1/T_i s)$ has been empirically tuned based on experimental optimization in closed loop using the facilities, offered by the DCS. For an "operating column" it has parameters $K_p = 1.6$ and $T_i = 9$, min ($T_i = 540$, s) and an exponential noise filter $F(s) = (T_f.s + 1)^{-1}$ for the level signal with time constant $T_f = 0.2$, min. In washing mode the PI controller parameters are respectively changed to $K_p = 2.7$ and $T_i = 12$, min. The controller output U is connected to the analog output of the DCS to control the butterfly valve DN150 type LW7LBAA150 through intelligent positioner (NELES ND9000 Intelligent valve controller, 2015; NELDISC Metal seated butterfly valves, 2007), powered by the signal line of 4–20, mA and also connected to instrumentation air for driving the actuator. The actuator is a double acting pneumatic cylinder, which turns the butterfly valve on 90 degrees.

The plant input is the controller output U and the controlled plant output is the measured level H by the help of the microwave radar transmitter, both normalized in the range [0, 100], %. The main disturbance is the pressure P of the precarbonated solution before the valve which varies in a random way. Depending on the prepared amount of precarbonated solution which has to be distributed among the different CCls in working mode, the reference for the level varies within the range [30, 70], %. The block diagram of the closed loop system with the PI controller is shown in Fig. 1.

The recorded step responses with respect to the level H_{ex} and the control U_{ex} from real time linear level control for reference changes above and below the nominal reference $H_r = 50\%$ are shown in Fig. 2. From these step responses it can be concluded that the dynamic accuracy of the control system has to be improved and also the high frequency oscillations of the control action have to be reduced in order to protect the final control elements (the valve and the pneumatic actuator) from intensive ageing and wearing these oscillations cause. A nonlinear TSK-based PDC controller which has a simple design and algorithm, based on local linear controllers and methods for design of linear control systems, is suitable to better respond to the immanent plant nonlinearity and the plant model uncertainties thus improving the control system performance by smooth and energy efficient control. Besides, it is easy to implement in any PLC for real time control.