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State Controller Design in Programmable Logic Controllers

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Introduction

The training panel (see Fig. 1) simulates the process of a chemical reaction vessel model, including the ability to control the temperature and the feeding level. Together with the control function of the programmable logic controller it is possible to solve various teaching exercises of control engineering.

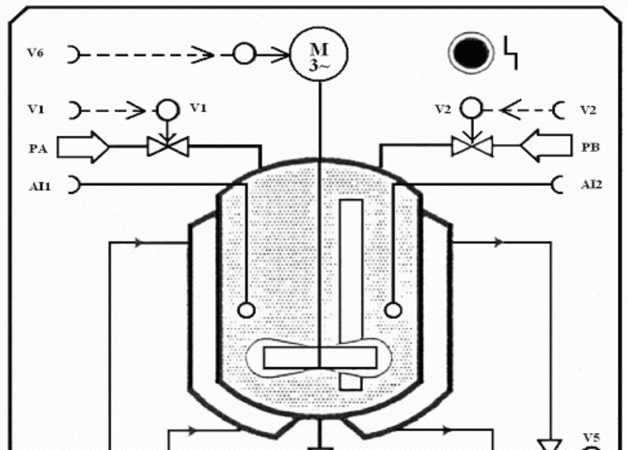

Fig. 1. The process of a chemical reaction vessel

The reaction vessel is equipped with a double-walled jacket. A heating and cooling medium can be pumped through the interstice of the vessel. The drainage quantity of the final product C1 (PC), i.e. the draining of the vessel, is continuously adjustable via an analog control signal AV1 (actuator). The analog valve AV2 is used as the actuator in order to continuously adjust the inflow quantity of the heating medium. The heating medium circulation is only active when the binary outflow valve V5 opens towards the direction of the condenser and when the inflow valve AV2 is open. The binary valve V3 opens the inflow of the cooling medium. The cooling medium circulation is only active, when the binary inflow valve V3 and the binary outflow valve V4 are open.

The temperature of products A1 and B1 (via valves V1 and V2) as well as the temperature of the medium in the cooling circuit (V3 and V4) are simulated with 5 degrees Celsius. The temperature of the medium in the heating circulation is simulated with 100 degrees Celsius (AV2, V5). The limiting temperature values, for the final product C in the vessel, are maximum 100 degrees Celsius or minimum 5 degrees Celsius. In case the cooler products A1 or B1 are added to the already warmed up final product C1, then a temperature fall happens according to the mixing ratio of the cold and warm vessel substances.

The vessel has the ability to enable natural heat exchange with the environment, which is always active, even when no heating or cooling functions are carried out. The environmental temperature is set to +20 degrees Celsius and becomes active immediately after switching on the panel. The transfer function of the chemical reaction vessel model heat transmission [1] is

$$W(s)=\frac{K_s}{(1+T_1 s)(1+T_2 s)}\,. \tag{1}$$

The time constant T_1 of the two heat transmission time constants T_1 and T_2, is linear dependent from the feeding level and the agitator status. T_1 varies around the factor 8 between the empty and fed vessel and in addition to that, varies around the factor 2 dependent on the fact whether the agitator V6 is switched „On“ or „Off“. Time constant T_1 =73s. Time constant T_2 =10.3s. The time constants of the sensors are negligible compared to the other time constants and are therefore not simulated. K_s=8 for the heating action and K_s=-15 for the cooling action.

The object’s state-space model and controllability

The state of a system at any time t_0 is the minimum set of numbers $x_1(t_0)$, $x_2(t_0)$, …, $x_n(t_0)$ which, along with the input to the system for $t \geq t_0$, is sufficient to determine the behavior of the system for all $t \geq t_0$. In other words, the state of the system represents the minimum amount of information that is necessary to know about the system at time t_0. The most general form of system state equations is:

$$\begin{cases} x(t) = Ax(t) + Bu(t), \\ y(t) = Cx(t). \end{cases} \qquad (2)$$

Here x is an n-dimensional state vector; u is r-dimensional control vector, y is m-dimensional output vector, A is an mxn system matrix, B is nxr control matrix and C is mxn output matrix.

The chemical reaction vessel model is a second order system. The representation of the system (1) by the state variables (2) is obtained after calculating A, B, C matrixes

$$A = \begin{bmatrix} -\frac{1}{T_1} & 0 \\ \frac{1}{T_2} & -\frac{1}{T_2} \end{bmatrix}, \; B = \begin{bmatrix} \frac{K_S}{T_1} \\ 0 \end{bmatrix}, \; C = \begin{bmatrix} 0 & 1 \end{bmatrix}. \qquad (3)$$

According to eigenvalues of the matrix A, the open loop system is stable.

In many practical control problems it is common that not all state variables can be measured or controlled. Without an assumption of controllability and observability, such information would be useless. In case of a chemical reaction vessel model, only the control input and the output state (temperature) of the system can be measured. After obtaining a system model in the state space and after defining system observability, it is possible to reconstruct a non-measured state variable from the measured control input and output of the system [2].

To define system controllability, the following composite matrix has been created:

$$\begin{bmatrix} B & AB \end{bmatrix} = \begin{bmatrix} \frac{K_s}{T_1} & -\frac{K_s}{T_1^2} \\ 0 & \frac{K_s}{T_1 T_2} \end{bmatrix} = \frac{K_s^2}{T_1^2 T_2}. \qquad (4)$$

System (2) is controllable because the composite matrix (4) is nonsingular; i.e., its determinant is nonzero.

State controller design in Matlab environment

Below there are presented two state controllers design approaches for product temperature in the reactor vessel model control. In fact, the controllers obtained through the described procedure are generally good.

First of all in the state-feedback version of the linear quadratic regulation (LQR) problem let's assume that if not all x states can be measured they are still available for control. The state-feedback LQR controller is a simple matrix gain of the form

$$u(t) = -K \cdot \hat{x}(t)\,, \qquad (5)$$

here K is the mxn matrix given by the solution of the algebraic Riccati equation [3]. The controller gain K coefficients were chosen: k_1=0.6019, k_2=0.2809.

Second state controller design refers to the selection of the gain matrix K (5), using the pole placement method. The difficulty of this design consists essentially of the determination of the_feedback vector so that the n eigenvalues of the system matrix have the desired distribution. The error dynamics of the controller are given by the poles of

$$\det(sI - A + BK) = 0\,. \qquad (6)$$

The estimation error will converge to zero if the determinant has all its eigenvalues in the left-half of the s plane.

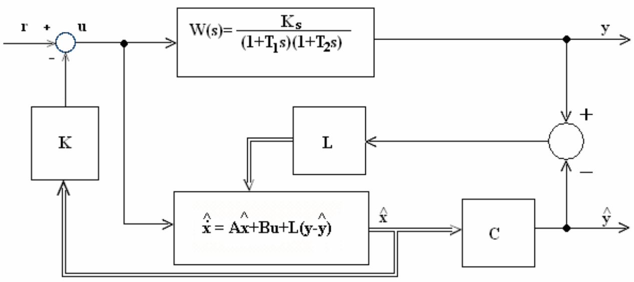

Fig. 2. A block diagram of the system with a state observer and a state controller

The dynamics of the controller must be much faster than the system itself, so it is necessary to place the poles at least five times further to the left than the dominant poles of the system. The controller gain K coefficients were chosen: k_1=364, k_2=72636. A simulated system block diagram is shown in Fig. 2.

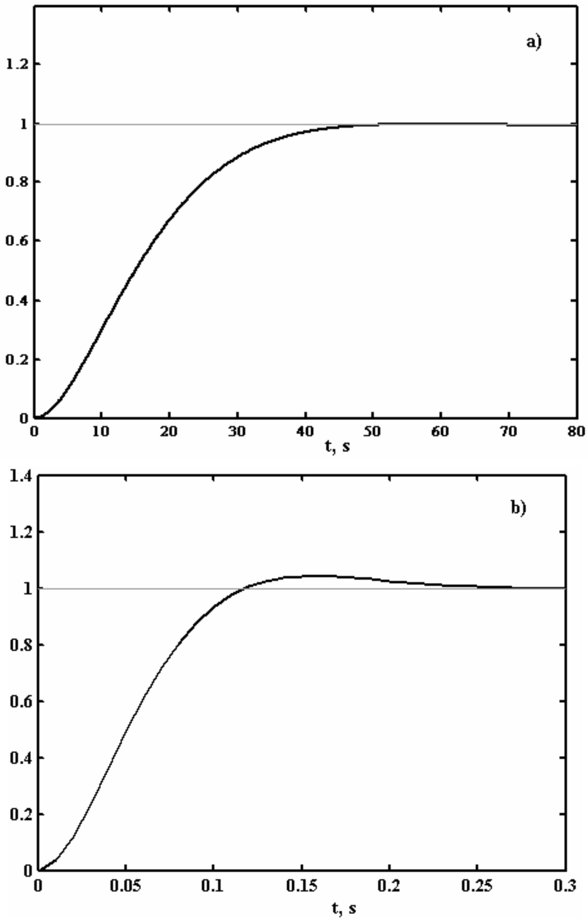

Fig. 3. The response of a closed loop system with a state controller (designed a) using LQR; b) pole placement method) to the unit step input

Simulation results showed that both controllers allow decreasing the temperature settling time distinctly comparing to an open loop system [2]. Only LQR controller was tested in the programmable logic controller (PLC), because the LQR controller output fits into the output range of the PLC analog output module.

State controller design in programmable logic controller

Programmable logic controllers are electronic devices used for automation of industrial processes, such as control of machinery on factory assembly lines. Very complex process control, such as used in the chemical industry, may require algorithms and performance of high-performance PLCs. Recently, the international standard IEC 61131-3 has become popular in PLC programming. A designed state controller (see Fig. 4) was programmed with Unity Pro software using FBD programming language [4]. The fundamental concepts of PLC programming are common to all manufacturers, so the state controller implementation program that is presented here is interchangeable between different makers of the programmable logic controllers.

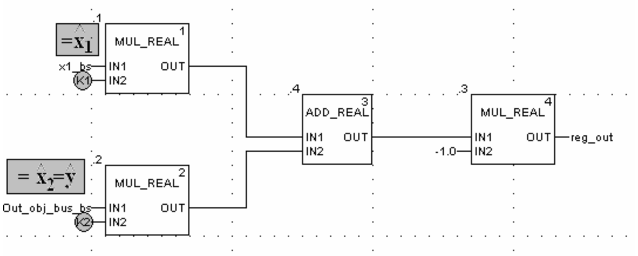

Fig. 4. A PLC program that is implementing a state controller in the FBD language

A designed state controller and a chemical reaction vessel model research were done using the scheme presented in Fig. 5.

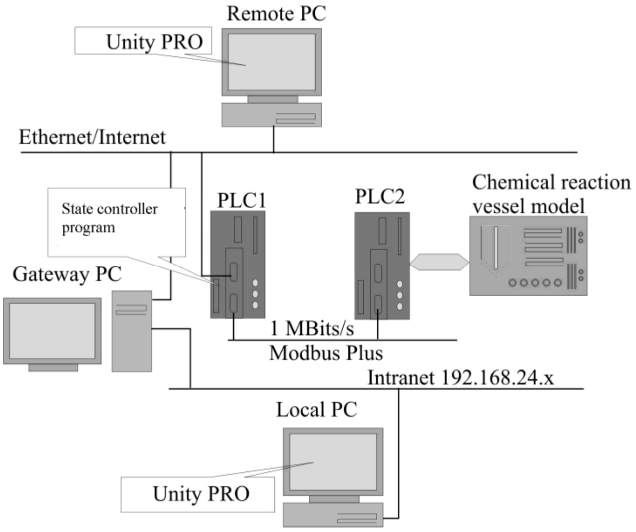

Fig. 5. A state controller and a chemical reaction vessel model research scheme

The inputs/outputs of a chemical reaction vessel model were connected to the PLC2 (Quantum CPU 113 03) outputs/inputs. PLC2 had a program which processed only the model inputs and outputs (measured temperature which was *y* and level; had mapped addresses to temperature control signal which was *u* and level control signal).

PLC1 (Quantum CPU 650 50) had a program which implemented a designed state controller and was responsible for the communications between PLC1 and PLC2. The PLC1 program controlled the level of the vessel also. PLC1 and PLC2 were interchanging data through Modbus Plus network every 100 ms.

An Ethernet PC with Unity Pro software had a connection to the PLC1, in order to supervise program states and to draw needed graphics.

A system response to the step reference signal at different working conditions has been researched.

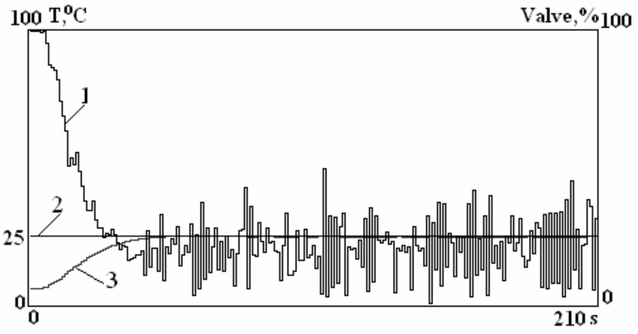

Fig. 6. System response to 25% step input, when the agitator V6 is switched „On“ and the vessel level is 50%; 1 – control signal, 2 – reference input, 3 – process variable

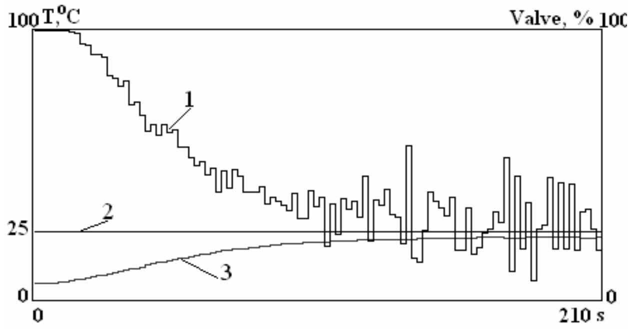

Fig. 7. System response to 25% step input, when the agitator V6 is switched „Off“ and the vessel level is 50% ; 1 – control signal, 2 – reference input, 3 – process variable

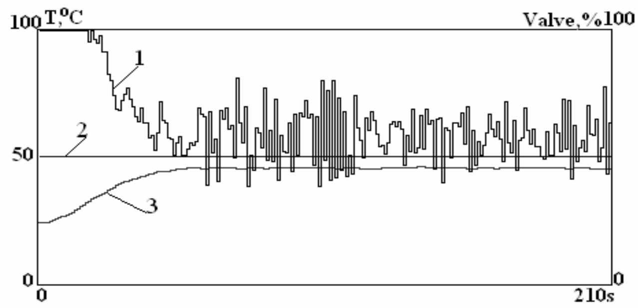

Fig. 8. System response to 50% step input, when the agitator V6 is switched „On” and the vessel level is 50%; 1 – control signal, 2 – reference input, 3 – process variable

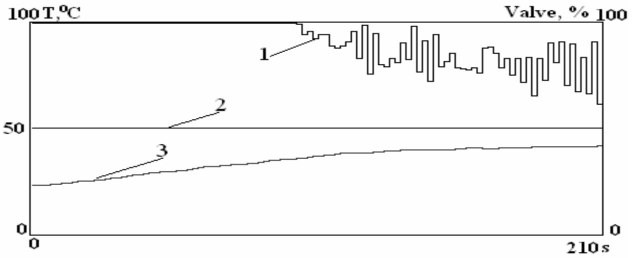

Fig. 9. System response to 50% step input, when the agitator V6 is switched „Off" and the vessel level is 100%; 1 – control signal, 2 – reference input, 3 – process variable

From the system responses (see Fig. 6-9) to the step input it can be concluded that after the settling time, the occurrence of the steady state error depends on the agitator V6 state and the limit time of the controller output. Also, it can be concluded that the vessel level influenced the temperature settling time, the same way the agitator V6 did. The controller output and the steady state error also are affected by the temperature measurement accuracy (it depends on the update time of the PLC analog modules, number of bits of analog digital and digital analog converters), PLC program cycle and data interchanging speed which causes a delay of the process and a manipulated variable.

Conclusions

A study of the state controller design in a programmable logic controller has been performed. The following observations were made based on such results: a state controller in Matlab performs better than the controller in the PLC; the simulation and experimental results seem to justify the design concept of a state controller in the PLC. Perhaps an even more important fact is that LQR controller is robust to the process uncertainty.

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There are presented two state controllers design approaches for product temperature in the reactor vessel model control. First of all in the state-feedback version of the linear quadratic regulation (LQR) problem were assumed that if not all *x* states can be measured they are still available for control. Second state controller design refers to the selection of the state controller gain matrix, using the pole placement method. Designed state controllers were tested in Matlab environment. Finally, only LQR controller was tested in the programmable logic controller (PLC). From the system responses to the step input it can be concluded that after the settling time, the occurrence of the steady state error depends on the reactor vessel agitator state and the limit time of the controller output. The following observation was made based on such results: the simulation and experimental results seem to justify the design concept of a state controller in the PLC. Il. 9, bibl.4 (in English; summaries in English, Russian and Lithuanian).

Л. Балашявичюс, В. С. Янушявичюс, С. Закарайте. Проектирование регулятора состояния в программируемых логических контроллерах // Электроника и электротехника. – Каунас: Технология, 2008. – № 1(81). – С. 19–22.

Представлены два способа проектирования регуляторов состояния для управления температуры продукта в модели реактора. При проектировании линейного квадратного регулятора состояния (ЛКРС) считается, что хотя не все состояния *x* наблюдаемы, все они управляемы. Во втором случае проектирование регулятора состояния сводится к выбору матрицы усиления путем подбора корней системы. После проверки регуляторов в Матлабе, в программируемом логическом контроллере (ПЛК) реализован ЛКРС. По реакциям системы на входной сигнал установлено, что после переходного процесса статическая ошибка возникает из за состояния мешалки и времени ограничения управляющего сигнала. Основываясь на полученных результатах можно утверждать, что резултаты моделирования и эксперимента подтверждают идею проектирования регулятора состояния в ПЛК. Ил. 9, библ. 4 (на английском языке; рефераты на английском, русском и литовском яз.).

L. Balaševičius, V. S. Januševičius, S. Zakaraitė. Būsenos reguliatoriaus projektavimas programuojamuosiuose loginiuose valdikliuose // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2008. – Nr. 1(81). – P. 19–22.

Pateikti du būsenos reguliatoriaus, skirto produkto temperatūrai reaktoriaus talpyklos modelyje valdyti, projektavimo būdai. Projektuojant tiesinį kvadratinį būsenos reguliatorių (TKBR), laikoma, kad, nors ne visos būsenos *x* yra stebimos, tačiau jos yra valdomos. Antruoju atveju būsenos reguliatoriaus projektavimas apima stiprinimo matricos parinkimą sistemos polių išdėstymo metodu. Patikrinus suprojektuotų būsenos reguliatorių darbą Matlab aplinkoje, programuojamajame loginiame valdiklyje (PLV) sukurtas TKBR. Iš sistemos reakcijų į šuolinį signalą nustatyta, jog, pasibaigus pereinamajam procesui, statinės paklaidos atsiradimą lemia valdančiojo signalo ribojimo laikas ir maišyklės būsena reaktoriaus talpykloje. Remiantis gautais rezultatais galima teigti, jog modeliavimo ir sistemos valdymo su PLV rezultatai patvirtina būsenos reguliatoriaus projektavimo programuojamuosiuose loginiuose valdikliuose idėją. Il. 9, bibl.4 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).