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Scientific paper

An inverse model of the fuzzy logic controller of the distillation column

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Abstract

In this paper identification and nonlinear control fuzzy system to the variation of the state variables over time were investigated. In order to perform the state prediction necessary to the fuzzy logic controller the system was developed based on input/output data. As a case study a distillation packed column was used. The controller has been based on the process inverse dynamic control. The aim of this investigation was building more robust and accurate control and improving noise handling. The dynamic response has been applied to predict and control the distillate composition and distillate flow rate to feed flow rate and feed composition disturbances. The main contribution of this paper is nonlinear fuzzy control function of the outputs with reflux flow rate as manipulative variable. The obtained results show improving products quality control with time delay, determine optimum set points, and a troubleshooting day to day operating problem.

Keywords: Inverse dynamic model, fuzzy control, manipulative variable, time delay.

1. Introduction

Some studies of engineering applications of fuzzy set theory have reported that, by replacing a conventional controller with nonlinear fuzzy controller, better performance and local stability can achieved. In general, fuzzy logic control systems may have better system performance (Zadeh,1983; Korn,1993) It is true that the weighting factors are functions of both the parameter of the plant under control and performance index of the closed loop system. These rules and formula are hepful in eliminating the most time consuming trial and error method in the synthesis and design of fuzzy control systems (Savković-Stevanović et.al.,2008).

A fuzzy controller uses fuzzy logic to perform real time comparisons between incoming data and historical data and can resolve fuzzy matches, error correction and image recognition.

In this paper modeling of the fuzzy control system was illustrated on a distillation plant. The plant input and output are considered during the simulation. The dynamic responses of the output variables control loops to a random disturbance with varying amplitude were examined.

2. Process distillation variables definition

For a distillation column, input variables might include feed rate F and feed composition x_F, disturbances, and reflux flow L_R and heat input to the reboiler Q_r as manipulative variables. Output variables might include overhead distillate flow rate D and composition x_D, bottoms product flow rate B and composition x_B, holdups M, and flow rates of the vapor V and liquid L on any or all of the trays.

One physical stream may be considered to contain many variables its rate, its composition, its temperature, etc. .

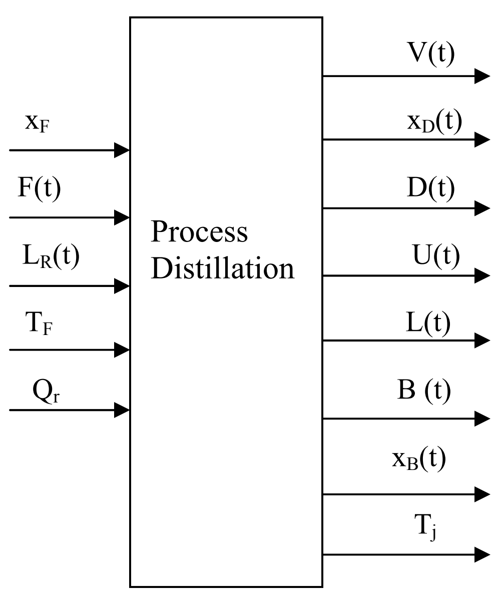

Figure 1. Dynamic variables

In this study as manipulative variable is considered reflux rate $L_R(t)$. Disturbances were made in feed rate F(t) and feed composition $x_F(t)$, As controlled variables were considered distillation composition $x_D(t)$ and distillate rate D(t).

Control transfer functions with time delay in feed forward loop for distillation column were studied by Rippin and Lamb,and Lupfer and Parsons (Lupfer and Parsons,1962) and (Savkovic-Stevanovic ,1987; Savković-Stevanović et.al.,1991). In this paper fuzzy logic control was illustrated by inverse loops.

The qualitative model for systematic cause - event analysis was made, and variables discrete state were defined (Savkovic-Stevanovic,1999;2002;1995):

Input variables (low, medium, high)
Output variables (low, medium, high)
Control variables (increasing, slow increasing, normal, slow decreasing , decreasing).

3. Multivalued fuzzy logic

It incorporate the imprecision inherent in many real world systems, including human reasoning, by allowing linguistic variables classification such as *big, high, slow, medium*, *near zero*, or *too fast*. Unlike binary logic, fuzzy system do not restrict a variable to be a member of a single set, but recognize that a given value may fit to varying degrees, into several.

Fuzzy systems operate by testing variables with IF-THEN rules, which produce appropriate responses. Each rules then weighted by a degree of fulfillment of the rule invoked, this is a number between 0 and 1, and may be thought of as probability that a given number is considered to be included in a particular set. A wide variety of shapes is possible fulfillment functions, with triangles and trapezoids being the most popular. Membership functions for this study were of the form:

$$\mu(x,m,s,p) = \exp(-(|x-m|)/s)^{p}) \quad (1)$$

where m, s, and p are user chosen parameters and x is the values to be tested. The function was chosen because of its flexibility, by changing m, s, and p whole families of different functions can be obtained. For p=2 this is an non-normalized Gaussian density with mean *m,* and standard deviation *s*. A sample of the functions obtains by varying the *p*.

The system operates by testing rules of different types:

IF x_i is high AND y_i is low THEN u_{ij} is slow increasing. etc..

The degree of fulfillment for such a rule in this study was chosen to be the minimum of the degrees of fulfillment of the antecedent clauses. The total output of the control system is calculated as weighted sum of the responses to all *n* rules outputs.

In this paper the meaning of the linguistic values is defined by left – right type membership function (Savković-Stevanović et.al,2008).

4. Inverse fuzzy models control

At the inverse dynamics the control variables, in order to make plant output, follow the desired set-point. These inputs can be randomly generated, but they must preferable cover all the input domain. The plant input and output are recorded during the simulation.

For a manipulative variable u(k) and controlled variable Y(k), and s(k+1) as desired point value, a control system is shown in Fig.2 and control function is given by Eq.(2).

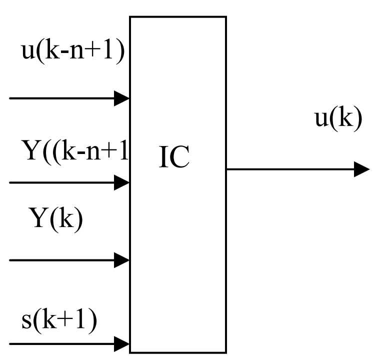

Figure 2. Inverse control model

The inverse dynamics of the plant is modeled by applied the input from the initial state of the plant to the final state of the plant [7]-[9]. The weighting factors are functions of both the parameter of the plant under control and performance index of the closed loop system.

$$u(k) = f\{Y(k), Y(k-n+1), s(k+1), u(k-n+1)\} \quad (2)$$

In Fig.3 distillate flow control system model is shown,

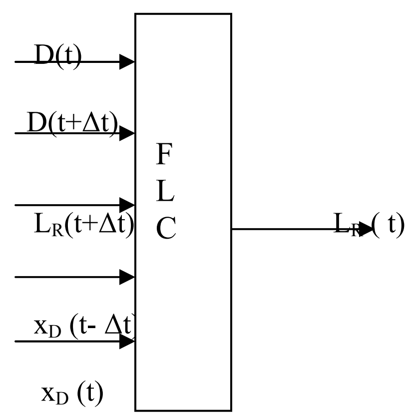

Figure 3. Distillate flow control system model

Distillate flow control system model and dynamic control function for distillate flow rate is given by Eq.(3).

$$L_R(t)=f(D(t), D(t+\Delta t), L_R(t-\Delta t), x_D(t-\Delta t), x_D(t)). \quad (3)$$

Distillate composition control systems is shown in Figure 4 and control function is given by Eq.(4). Control function for distillate composition is,

$$L_R(t)= f(D(t), L_R(t-\Delta t), x_D(t-\Delta t), x_D(t), x_D(t+\Delta t)). \quad (4)$$

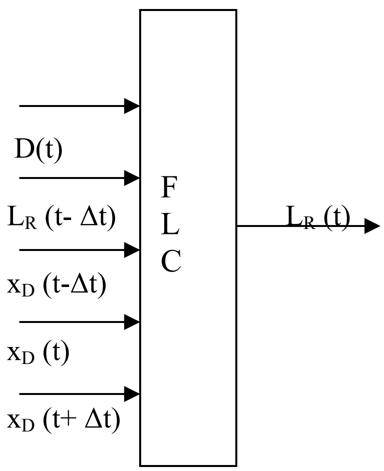

Figure 4. Distillate composition control system model

Many other systems were design for control as shown in Figure 5 and Figure 6. An inverse model for distillate control system with feed rate disturbance is shown in Figure 5 and by Eq.(5).

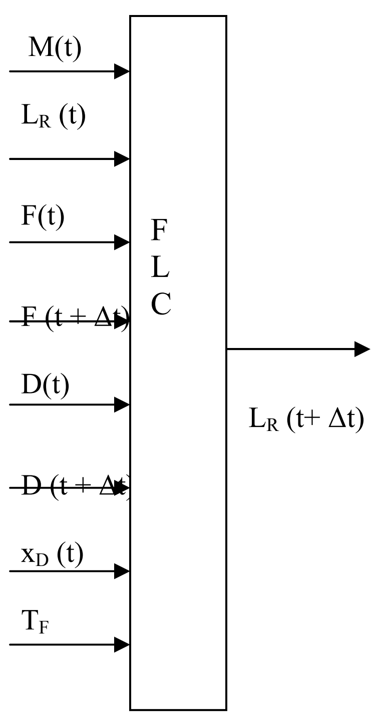

Figure 5. An inverse model for distillate flow rate control system with feed rate changes

A control function for distillate composition is,

$$L_R\ (t+\Delta t)=f(D(t),\ D(t+\Delta t), F(t),\ F\ (t+\Delta t),\ x_D(t),\ x_F\ (t),\ T_F\ (t),\ L_R\ (t),\ L_R\ (t-\Delta t),\ U(t)) \quad (5)$$

An inverse model for distillate composition control system with feed composition disturbance is shown in Fig. 6 and by Eq.(6).

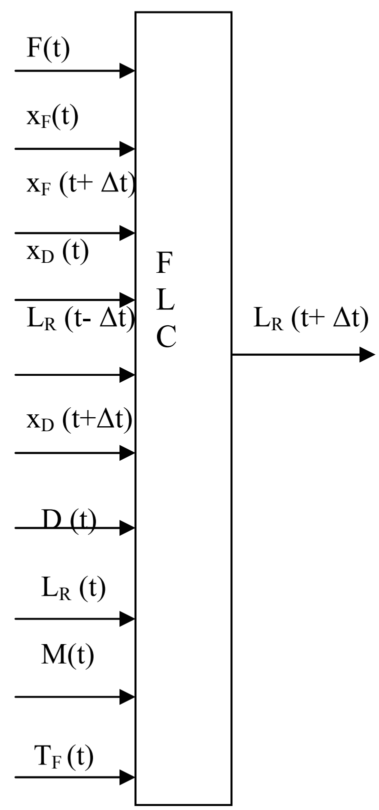

Figure 6. Distillate composition control system model with feed composition changes

A control function for distillate composition is,

$$L_R\ (t+\Delta t)=f(F(t),\ x_F(t),\ x_F(t+\Delta t),\ T_F(t), x_D\ (t), x_D\ (t+\Delta t),\ D\ (t),\ L_R\ (t),\ L_R\ (t-\Delta t),\ M(t)) \quad (6)$$

5. Fuzzy rules sets for distillation plant control

A fuzzy control system was generating using numerous set of rules. Some of them are following:

Rule set number 1:
IF L_R (t) is decreasing THEN D(t+Δt) is increasing
following x_D(t).
IF L_R (t) is increasing THEN D(t+Δt) is decreasing following x_D(t).

Rule set number 2:
IF L_R (t) is decreasing THEN x_D(t+Δt) is decreasing
following D(t).
IF L_R (t) is increasing THEN x_D(t+Δt) is increasing following D(t).

Rule set number 3:
IF L_R (t+Δt) is high AND F(t) is high THEN D(t+Δt) is normal following x_D(t).
IF L_R (t+Δt) is low AND F(t) is high THEN D(t+Δt) is increasing following x_D(t).

Rule set number 4.
IF L_R (t+ Δt) is medium AND x_F(t) is high THEN x_D (t+Δt) is increasing following D(t).
IF L_R (t+ Δt) is low AND x_F(t) is high THEN x_D (t+Δt) is normal following D(t).

6. A case study

In this paper a laboratory distillation plant with ten theoretical stages for ethyl-acetate recovery from the mixture was used as shown in Figure 7. The main state variables characterizing of the process are the feed flow rate F, ethyl-acetate composition in the feed x_F, ethyl-acetate composition in the distillate x_D, reflux flow rate L_R, bottoms flow rate B,and bottoms composition x_B.

A dynamic model for a distillation column control can be obtained using of the first principle modeling approach.

Column total material balance,

$$F - D - B = \frac{dM_{tot}}{dt} \qquad (7)$$

Column component balance,

$$Fx_{F,i} - Dx_{D,i} - Bx_{B,i} = \frac{dMx_{i,tot}}{dt} \qquad (8)$$

Column total energy balance,

$$Fh_F - Dh_D - Bh_B + Q_r - Q_c = \frac{dU_{tot}}{dt} \qquad (9)$$

Total material balance for stage j,

$$L_{j+1} + V_{j-1} - L_j - V_j = \frac{dm_j}{dt} \qquad (10)$$

Total energy balance for stage j,

$$L_{j+1}h_{j+1} + V_{j-1}H_{j-1} - L_jh_j - V_jH_j = \frac{dU_j}{dt} \qquad (11)$$

Component material balance per stage j,

$$L_{j+1}x_{i,j+1} - V_{j-1}y_{i,j-1} - L_jx_{i,j} - V_jy_{i,j} = \frac{dm_{j,i}}{dt} \qquad (12)$$

where $R_{LD} = \frac{L_R}{D}$ is reflux ratio, and

L_R = D R_{LD} is liquid flow rate, V is vapor flow rate, F is feed, D is distillate flow rate, B is bottoms flow rate, M is total holdup and m is holdup on the stage, H-enthalpy of the vapor phase, h is enthalpy of the liquid phase, x liquid phase composition, y is vapor phase composition, U is heat hold up, Q_r is reboiler heat and Q_c condenser heat. By the Eq.(7)- (9) simulation operation was performed for different conditions. The steady state parameters for examined process are given in Table 1.

Table1. The steady state parameters

Feed flow rate F, mole/s	3.160
Ethyl-acetate composition in the feed x_F, mole/mole	0.200
Distillate flow rate D, mole/s	1.660
Ethyl-acetate distillate composition x_D, mole/mole	0.800
Reflux flow rate L_R, mole	6.100
Bottoms flow rate B, mole/s	1.500
Hold up M, moles	2.000
Pressure, bar	1
Temperature $T_{Bottoms}$, ^0C	90.00
Temperature T_{top} ^0C	77.00
Temperature T_F , ^0C	45.50

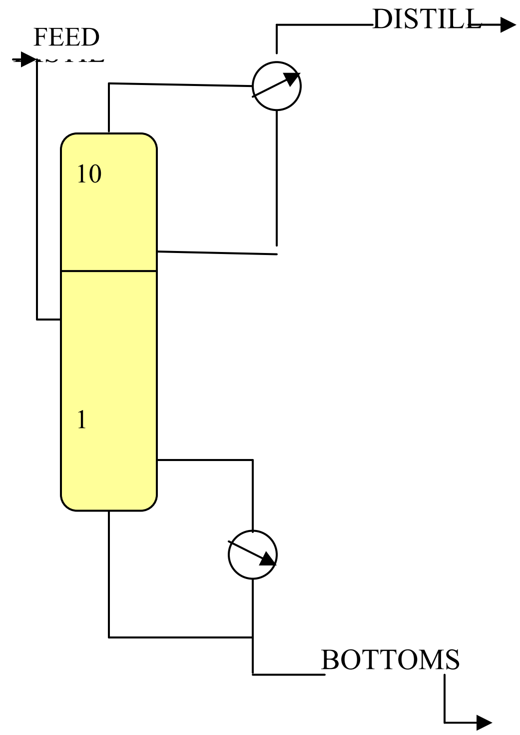

Figure 7. Scheme of the plant

6. Results and discussion

The dynamic responses of the flow rate and composition control loops to a random disturbance with varying amplitude were examined. In the first phase control provide without time delay. In the second step, the introduction of a time delay R, with R>1 has illustrated. This time delay has been taken as an integer number of sampling times. In Figure 8 disturbance in the reflux flow rate has shown.

The investigation is carried out during a time period from 0 to 2400s. The process inputs and outputs are considered during the simulation.

Figure 8 shows random disturbance in the reflux flow rate.

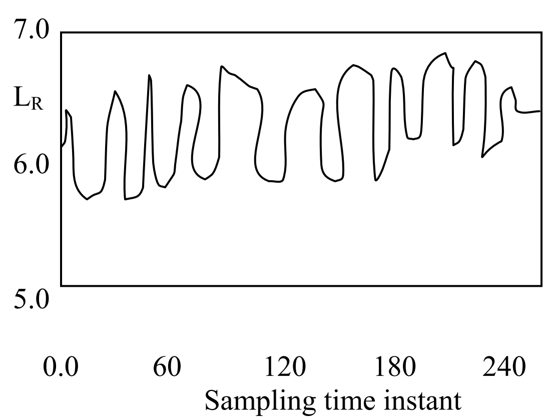

Figure 8. Disturbance in the reflux flow rate

Response of the distillate flow rate D(t) to this disturbance is shown in Figure 11.

Random disturbance in the feed flow rate is shown in Figure 9.

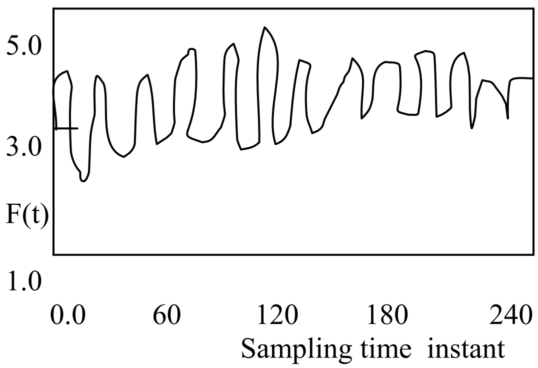

Figure 9. Random disturbance in the feed flow rate

Disturbance of the feed flow rate F(t) was made with constant feed composition x_F,(t) and temperature T_F (t). Responses of the reflux flow rate to this disturbances are shown in Figures 13 and 14.

In Figure 10 random disturbance to the feed composition is shown.

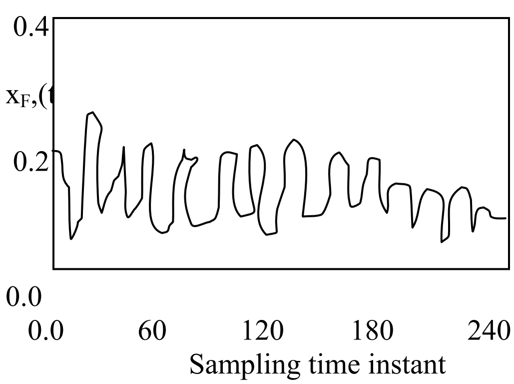

Figure 10. Random disturbance in the feed composition

Fig.11 shows dynamic response distillate flow rate for disturbance in the reflux flow rate without time delay (R=1).Fig.12 shows distillate composition x_D(t) changes to disturbance in the reflux flow rate without time delay.

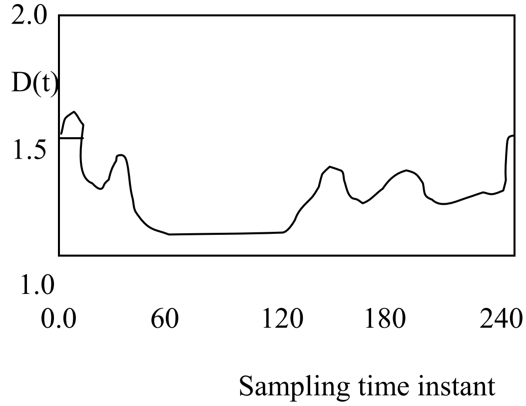

Figure 11. Dynamic response distillate flow rate for disturbance in the reflux flow rate without time delay (R=1)

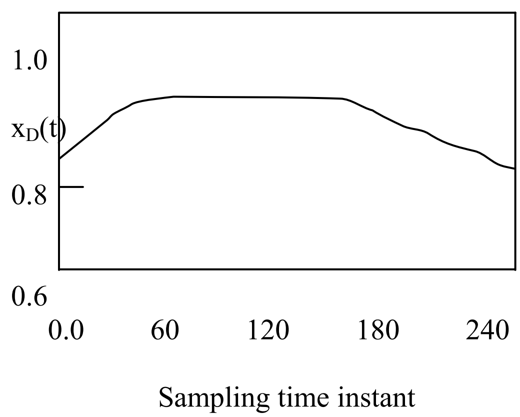

Figure 12. Response distillate composition to disturbance in the reflux flow rate without time delay (R=1)

Response of the reflux flow rate with time delay of R=3 to the feed flow rate disturbance is shown in Figure13. Figure 14 shows control response of the reflux flow rate to the feed flow rate with time delay of R=5.

The developed model based on fuzzy logic performed well for the wider operating ranges considered. It can be used with confidence for the on-line control.

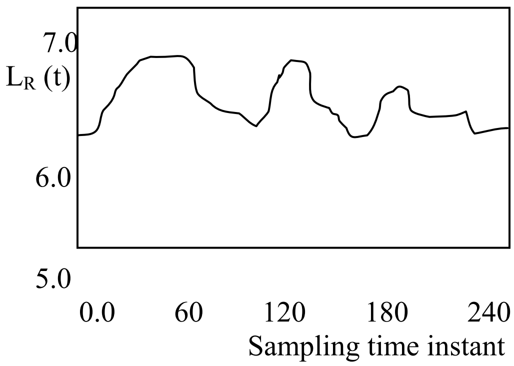

Figure 13. The reflux flow rate response to the feed flow rate with time delay of R=3

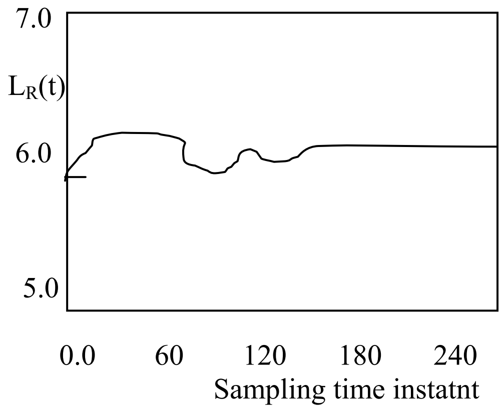

Figure 14. Response reflux flow rate to feed flow rate with time delay of R=5

7. Conclusion

In this paper inverse models of the fuzzy control are derived for distillate flow rate and quality control by reflux flow rate as manipulated variable. The fuzzy logic control system developed base on input/output data. The developed model performed well for the wider operating ranges considered and can be used with confidence for the on-line control. This paper shows ability to apply fuzzy controller for controlling a state variable in distillation plant. The non stationary characteristics of the process is handled by feeding, information of the state variables, and not only the control error, to the fuzzy controller. These results can be obtained in the other domain.

Acknowledgment. The authors wish to express their gratitude to the Fund of Serbia for financial support.

Notation

B-bottoms flow rate, mole/s
D-distillate flow rate, mole/s
H-enthalpy of the liquid phase. J/mole
h- enthalpy of the vapor phase. J/mole
L-reflux flow rate, mole/s
M-total hold up, mole
m-holdup per stage, mole
Q-external heat
R-time delay number
R_{LD}- reflux ratio
s-set point
T-temperature, ^{0}C
U- energy, J
u-manipulated variable
x-liquid composition, mole/mole
Y-control variable
y-vapor phase composition, mole/mole

Index

B-bottoms
c-condenser
D-distillate
F-feed
L-liquid phase
V-vapor phase
r-reboler

Greek symbol

Δt-sampling interval
j-stage
i-component

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IZVOD

INVERZNI MODEL REGULATORA DESTILACIONE KOLONE U USLOVIMA NEIZVESNOSTI

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U ovom radu ispitivana je identifikacija fazi nelinearnog sistema na promenu stanja promenljivih sa vremenom. U cilju predikcije stanja potrebnih za fazi-logički regulator razvijen je sistem na bazi ulazno-izlaznih podataka. Kao slučaj za ispitivanje korišćena je jedna destilaciona kolona. Cilj ovog istraživanja je izgradnja robustnije i tačnije regulacije i poboljšanje otklanjanja šumova. Dinamički odziv je primenjen na predikciju i regulaciju sastava destilata i protoka destilata na poremećaj sastava i protoka ulazne šarže. Glavni doprinos ovog rada je nelinearna fazi regulaciona funkcija izlaza, sa refluksnim protokom kao manipulativnom promenljivom. Dobiveni rezultati pokazuju poboljšanje kvaliteta regulacije produkta sa vremenom kašnjenja, optimalni početni set, i otklanjanje opeativnih problema iz dana u dan.

Ključne reči: Inverzni dinamički model, regulacija u uslovima neizvesnosti, manipulativna promenljiva, vreme kašnjenja