MATLAB Real-Time Two-Level Fuzzy Control of Nonlinear Plant

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Abstract: - The aim of the recent paper is to develop a real-time system for a fuzzy two-level control of an electrical model of a nonlinear plant. The real world plant is the anaerobic digestion of organic waste in wastewater treatment, where the biogas production rate is to be controlled via the input dilution rate under variable organic loading and plant parameters. The plant characteristics in different operating points are modelled on an electronic FESTO trainer, based on operational amplifiers. The fuzzy controller is designed using Fuzzy Logic Toolbox of MATLAB and completed in Simulink. The electrical plant model is controlled in MATLAB real-time environment, using electronic board PCI-6014 to connect the plant model output to the Simulink fuzzy controller via analogue input block, and the controller's output - to the plant model input via analogue output block. The main contributions are: a developed two-level Mamdani real-time controller for a nonlinear plant, a real-time control of electrical model of the plant and study of the fuzzy system performance improvements by comparison with the performance of a system with PI controller.

Key-Words: - Real-time fuzzy supervisory control, anaerobic organic waste degradation, MATLAB, stability

1 Introduction

Most industrial processes are complex nonlinear time-varying plants, difficult to model and control. Therefore advanced control approaches are used that combine knowledge of plant experts, measurements and operational experience to satisfy the high performance demands to the contemporary control systems accounting for plant nonlinearity, uncertainty and complexity and saving effort for building of accurate and simple plant classical mathematical model.

The fuzzy sets theory offers a methodology for representing of heuristic expert knowledge in a computable way by linguistic labels implemented in linguistic rules thus dealing with uncertainties and avoiding complex mathematical relationships [1, 2]. The fuzzy inference process involves membership functions (MFs), fuzzy logic operators mainly "and" and "or" and knowledge in if-then rules. It has been successfully applied to modelling, prediction and control of various complex processes [1-7].

The tuning problem in the fuzzy control is successfully overcome by a second level supervisory Mamdani-type controller for autotuning of the scaling coefficients [3]. The system performance improvements have been confirmed via simulations. However, the real world application is still on trial. A step towards it is to apply the two-level fuzzy approach in real-time control of a physical model of a nonlinear plant using a Simulink fuzzy controller and MATLAB real-time facilities [8, 9].

The aim of the recent investigation is to design and study in MATLAB environment a real-time fuzzy two-level system for the control of an electrical plant model for the biogas production rate via the dilution rate in the anaerobic digestion of organic waste in wastewater treatment and to compare the fuzzy system performance with the performance of a conventional PI controller system.

2 Problem Statement

The anaerobic digestion (methane fermentation) is considered one of the most promising methods for treating organic wastes, providing clean technology and energy recovery. It includes conversion of organic litter in absence of oxygen into safely exposable in the environment substances through a number of complex bacterial reactions.

There are three principal byproducts of anaerobic digestion: 1) biogas mostly of methane and carbon dioxide, which can be used to generate electricity; 2) rich in nutrients liquid, utilized in fertilizers; 3) organic material, comprised largely of lignin and chitin, but also of a variety of plastics and mineral components in a matrix of dead bacterial cells, used as compost or in low grade building products such as fiberboard.

The anaerobic digestion is often regarded as a three – phase conversion of organic waste into biogas [10, 11] – hydrolysis, acidogenesis and methanogenesis. The models used are nonlinear both in terms of parameters and variables making the classical identification and control theory inapplicable.

In recent years more and more complex mathematical models are being introduced in order to better present the biodegradable processes [10, 11]. Here for the purpose of control of the biogas production rate the fifth order Barth-Hill nonlinear model is used:

$$\begin{cases} \frac{dS_o}{dt} = -DS_o - \beta X_1 S_o + DY_p S_{oi} \\ \frac{dX_1}{dt} = (\mu_1 - k_1 - D)X_1 \\ \frac{dS_1}{dt} = -DS_1 + \beta X_1 S_o - \frac{\mu_1 X_1}{Y_1} \\ \frac{dX_2}{dt} = (\mu_2 - k_2 - D)X_2 \\ \frac{dS_2}{dt} = -DS_2 + Y_b \mu_1 X_1 - \frac{\mu_2 X_2}{Y_2} \\ Q = Y_g \mu_2 X_2 \\ \mu_1 = \frac{\mu_{1\max} S_1}{k_{s1} + S_1}, \mu_2 = \frac{\mu_{2\max} S_2}{k_{s2} + S_2} \end{cases}, \quad (1)$$

where: S_0 is the concentration of soluble organics (mg/l); X_1 – of acidogenic bacteria, mg/l; S_1 - of substrate for acidogenic bacteria, mg/l; X_2 – of methanogenic bacteria, mg/l; S_2 – of substrate for methanogenic bacteria, mg/l.

The output is the specific biogas production rate $y=[Q]$, l/l.d, $Q(0)=0.94$. The inputs are the control variable - the dilution rate D [$D\in(0, 0.3)$], d^{-1}, $D(0)=0.04$, and the disturbance – the influent organic concentration S_{oi}, [$S_{oi}, \in(30, 70)$], g/l.

The initial conditions for the state space vector are:

$$X(0)^{T} = [S_o(0), X_1(0), S_1(0), X_2(0), S_2(0)] = \\ = [10 \quad 0.36 \quad 0.18 \quad 15.66 \quad 0.18].$$

The vector of the parameters

$$q^T = [\beta\ Y_p \mu_{1\max}\ k_{s1}\ k_1\ Y_1\ \mu_{2\max}\ k_{s2}\ k_2\ Y_1\ Y_b\ Y_g]$$

consists of the coefficients β, d^{-1}, Y_p, mg/l, Y_b, mg/g and Y_g, l/mg, the maximal specific growth rate of acidogenic $\mu_{1\max}$, d^{-1} and methanogenic $\mu_{2\max}$, d^{-1} bacteria respectively, the yield coefficients Y_1, mg/mg and Y_2, mg/mg, the saturation k_{s1}, k_{s2}, mg/l and the decay k_1, k_2, d^{-1} coefficients for the corresponding bacteria. The nominal parameter values are:

$$q^{oT} = [1\ 2\ 0.4\ 1\ 0.02\ 0.006\ 0.4\ 1\ 0.02\ 1.1\ 40\ 1].$$

The plant characteristics from (1) are physically reproduced by means of operational amplifiers from a FESTO trainer by a series connection of three time lags with potentiometer-adjustable gains and time-constants. Thus the real world plant step responses at different operating points are modelled by different coefficients of the electrical plant model. The plant gain varies from K=2÷10. The electrical plant model is studied in real-

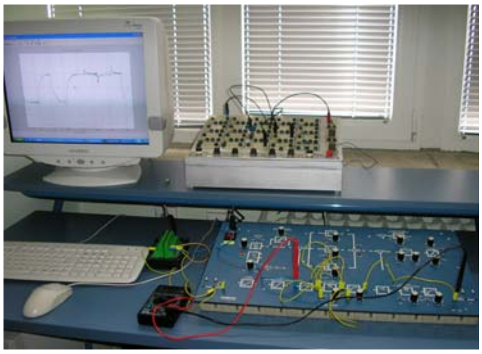

Fig.1. Experimental setup

time simulations by the help of the input and output channels of the NI board – PCI 6014 and the Real Time Workshop Toolbox of MATLAB, which converts external signals (voltage, etc.) from the FESTO trainer into MATLAB readable C-code and vice versa [12]. The experimental setup is represented in Fig.1. The signals are monitored by virtual scope and digital multimeter.

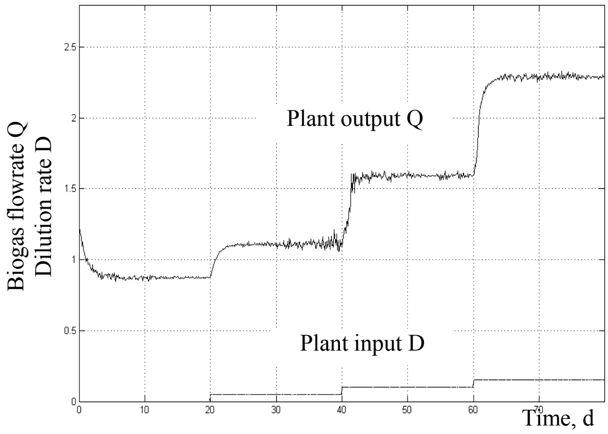

Fig.2. Plant step responses at different operating points

The plant nonlinearity is seen in the different magnitude of the settled responses to step inputs for D with equal magnitude, applied from different initial steady state points as shown in Fig.2.

The aim of the investigation is to design a real-time two-level fuzzy control system, which stabilizes the trainer output voltage that models the biogas production rate Q at desired references, corresponding to Q_r, at changes in the operating points and to estimate the system performance.

3 Design of a Real-Time Two-Level Fuzzy Control System

In [3] a two-level Mamdani controller with autotuning for a complex nonlinear plant is suggested. Simulations show that it ensures better control system performance in terms of shorter settling time and smaller overshoot than the performance of systems with ordinary fuzzy or PI controller. The two-level controller has, however, a

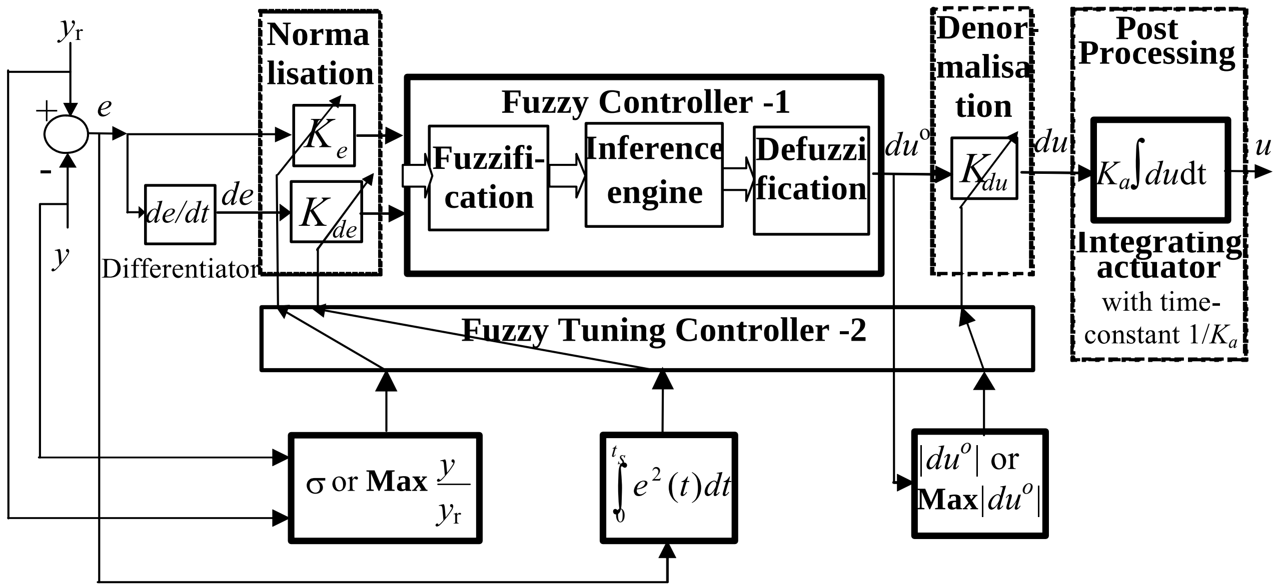

Fig.3. A two-level Mamdani fuzzy controller

complex structure. In Fig.3 is shown its principal functional block diagram.

The main fuzzy controller-1 has two inputs – the error e - $e = y_r - y$ as the difference between the reference y_r and the measured system output y, and the derivative of the error *de,* obtained at the output of a differentiator. The two inputs are normalized by means of the scaling coefficients K_e and K_{de}. The normalized controller output du^o after denormalization with K_{du} yields the incremental control action *du,* which is passed onto an integrating actuator to control the opening of the valve for the plant input flow.

The Mamdani fuzzy controller-2 for the supervisory tuning of K_e, K_{de} and K_{du} is composed of three fuzzy units. The input of the first unit in [3] is the overshoot σ, calculated for a test step response, and its output is K_e - the retuning is once after the test step response. The input of the second unit in [3] is the integral squared error $I = \int_0^{t_s} e^2(t)dt$, calculated till the settling time t_s, and the output is K_{de}. During a test step response K_{de} takes minimal possible value and at the end it is retuned and remains unchanged. The input of the third unit in [3] is $|du^o|$ and the output is K_{du} and the tuning is continuous. The rules for the three fuzzy units are based on the principle the bigger the input to the corresponding fuzzy unit – the smaller the scaling coefficient, so all scaling coefficients are smaller at higher input thus ensuring stability.

Concerning the peculiarities of the real-time control modifications of the input variables for the fuzzy controller-2 are suggested. First, the real world noise inference may cause continuous retuning of the scaling coefficients at each time step, which may result in oscillations in the control and in the plant output. Besides, the system may have no overshoot. Therefore, the controller's inputs for overshoot and $|du^o|$ are substituted with $\max \frac{y}{y_r}$ and max$|du^o|$ respectively - the maximum is retained till a new maximum at disturbance or reference and parameter change arises. Thus though K_e and K_{du} are continuously adjusted, this leads to slow and smooth changes. Second, the differentiator parameters should conform to the characteristics of the real world noise, the sample period and the requirement to ensure close to ideal differentiation. Accounting for the electrical plant model dynamic properties a sample period Δt=0.1, s is selected. For the specific plant model an actuator with K_a=0.1 is envisaged and the differentiator is tuned to yield a transfer function $\frac{2}{s+1}$.

The ranges and the membership functions for *e*, *de* and *du* are specified out of empirical rules for the electrical plant model in Fig.4, considering the magnitude of reference changes and disturbances and the limitation to real-world signals magnitude.

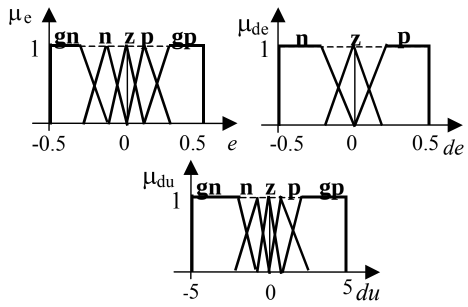

Fig.4. Membership functions of fuzzy controller-1

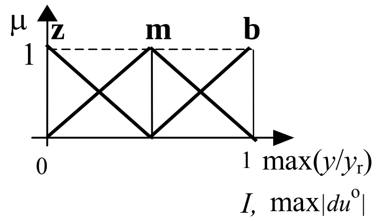

Fig.5. Membership functions of fuzzy controller-2

The MFs describe the following terms:

- "great negative"(gn), "negative" (n), "zero" (z), "positive" (p), "great positive" (gp) for *e* and *du*;
- "negative" (n), "zero" (z), "positive" (p) for *de*.

The MFs of the three units of the fuzzy controller -2 in Fig.5 describe the following linguistic terms for the input: **z** – for zero; **m** – for medium and **b** – for big. The coefficients K_e, K_{de} and K_{du} take the same linguistic values, denoted with **zk**, **mk** and **bk** with the same MFs.

In Fig.6 is given the Simulink part of the designed real-time fuzzy two-level control system.

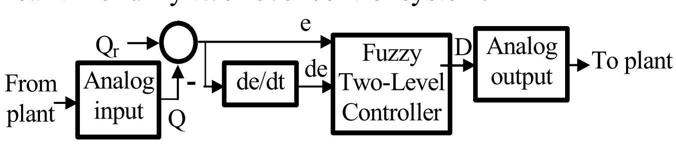

Fig.6. Simulink part of the fuzzy two-level control system

4 Real-Time Invetigations

Two real-time control systems are investigated – with the designed Simulink two-level Mamdani controller and with a Simulink PI controller with a gain K_p=0.8 and integral action time T_i=5, s, empirically tuned to ensure an overdamped transient response for nominal plant parameters – gain K=8, time-constant T=2.5,s and time delay τ=0.5, s.

The following experiments were carried out:

1) Initially the reference Q_r is kept to 0.94 for initial conditions to settle.

2) At t=20,s Q_r changes from 0.94 to 1.174.

3) At t=40,s Q_r changes from 1.174 to0.94.

4) After t=80,s the plant is subjected to parameter changes, simulating change of operating point. The plant gain K is changed in the following order: from 8 to 9.4; from 9.4 to 5.6; from 5.6 to 8 and from 8 to 2. The purpose of these changes is to observe how fast and efficiently the fuzzy or PI control system compensates the parameter disturbances. The transient responses are shown in Fig.7 and Fig.8.

The stability of the two systems is investigated using the phase-plane method. The phase trajectories of the system with Mamdani two-level controller and with the PI controller for different step responses (time sections) are shown in Fig.9 and Fig.10 and prove system stability for the applied inputs.

5 Conclusion

The main contributions of this paper can be systemized in the following way:

- an electrical model of a nonlinear time-varying plant is developed and studied by the help of a FESTO trainer and electronic NI board - PCI-6014 to simulate the characteristics of an anaerobic digestion of organic waste in wastewater treatment under various organic loading and microorganisms' state in MATLAB real-time environment;
- a real-time fuzzy two-level system for the control of the electrical plant model of the biogas production rate in the anaerobic digestion via the dilution rate is designed and studied using Real-Time Workshop and Simulink of MATLAB;
- a real-time system with a conventional PI controller for the control of the electrica plant model of the biogas production rate in MATLAB environment is designed and studied to provide a basis for comparison;
- the fuzzy control system performance is compared with the performance of a conventional PI controller system in order to estimate the advantages of real-time fuzzy two-level control;
- the stability of the two control systems is studied using the phase portrait approach;

The designed fuzzy two-level controller ensures faster transient responses at different operating points, less maximal dynamic deviation, greater robustness to parameter changes and disturbances as well as more smooth, economic and effective control. The phase trajectories of the fuzzy control system keep closer to the origin, which is an evidence of higher facilities to keep stability, greater robustness as well as overdamped and faster transient responses.

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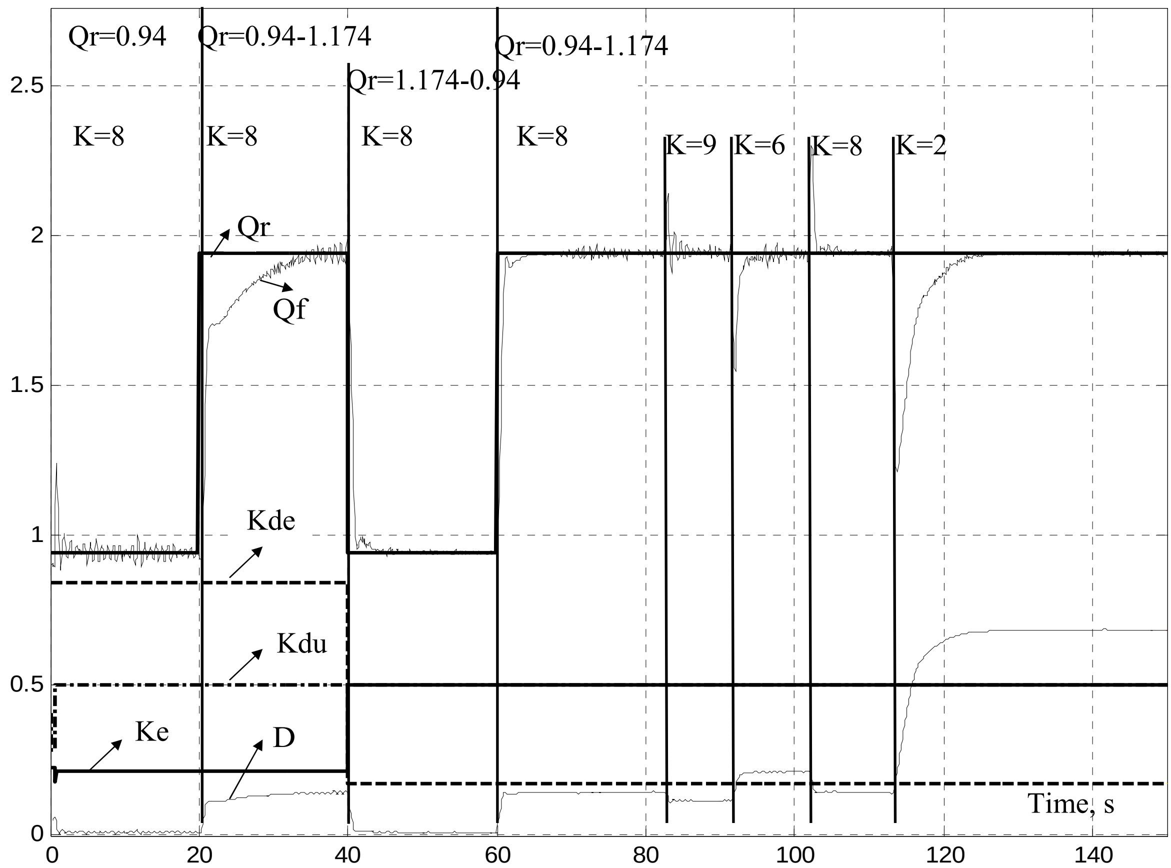

Fig.7. Step responses of the closed loop system with Mamdani two-level controller

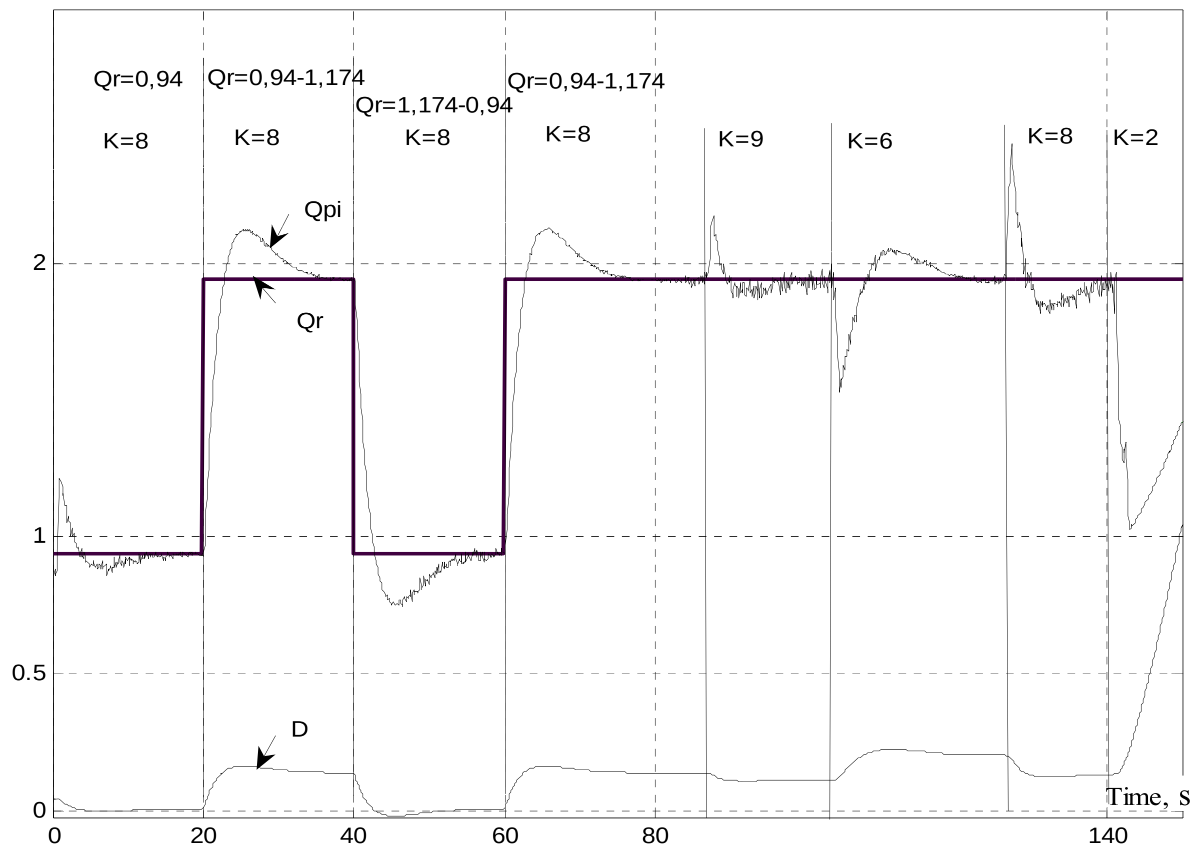

Fig.8. Step responses of the closed loop system with PI controller

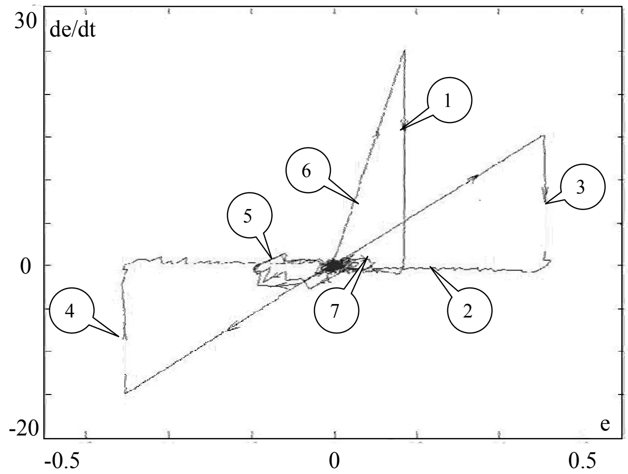

Fig.9 Phase trajectories of the system with Mamdani two-level controller

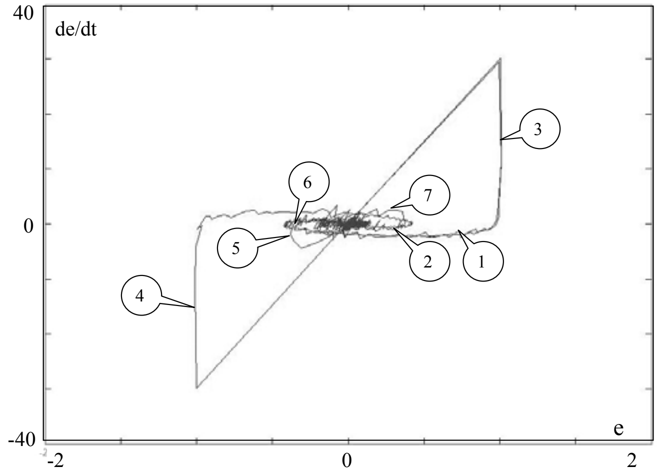

Fig.10 Phase trajectories of the system with PI controller

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