Design and Implementation of RST Controllers for a Nonlinear System

L.Thillai Rani[*], D.Sivakumar[*], D.Rathikarani[*], S.Suryakala[**]

[*]Faculty, Department of Electronics and Instrumentation Engineering, Annamalai University, Annamalai Nagar
[**]PG student, Department of Electronics and Instrumentation Engineering, Annamalai University, Annamalai Nagar
Chidambaram, India.
ltrani82@gmail.com

***Abstract*—This paper aims at developing an efficient controller for a nonlinear system. This necessitates identifying a near accurate model using the data acquired through real time experimentation conducted on the laboratory level process. An offline parametric estimation method is used to obtain discrete-time models for various operating regions. Three different digital polynomial controllers are designed and implemented to achieve the desired dynamics of the reference model. In order to obtain further improvement in the desired performance closed loop poles are relocated by Pole placement technique. The objective of this work also includes a comparative analysis of performances of the chosen system when implementing all these four strategies under different operating regions. The design and simulation studies are carried out in MATLAB/SIMULINK platform.**

***Keywords*—System identification, Recursive identification, Level control, Digital control, Model following, Pole placement.**

I. INTRODUCTION

With the increased dependency on computers to control industrial processes and to be on par with the recent trends in technology, process automation has been gaining widespread appreciation in almost all process industries. These industries involve liquid at some point or the other of its production process. So it is highly essential for accurate liquid level measurement and control at a desired level in most process industries. In order to improve upon the quality of any product and to achieve better plant operation there is a need for development of perfect controllers. To achieve an effective controller design, an accurate modelling of the process is very much needed.

System identification involves building a mathematical model of dynamic system based on a set of measured data and response samples [1]. The Recursive Least Squares (RLS) algorithm is one of the most popular identification technique which estimates the process in an efficient recursive manner. A modified algorithm based on RLS procedures with U-D factorization has been proved computationally more efficient than the classical RLS method [2].

Due to unforeseen reasons, parameters in the processes get changed significantly. Consequently, a general control system is to provide efficient control of the processes in spite of these parameter changes. The control of dynamic system in the presence of large uncertainties and constraints are of great interest for many applications. In such case, the controller has to take the appropriate control action [3]. Digital control is becoming increasingly important as most of the recent advanced controllers are implemented through digital devices. Plant identification and performance monitoring of control loops are done by manipulating the discrete data. In general, for digital control, it is convenient to use discrete time models [4],[5]. It is also important that in many cases tracking and regulation performances are to be decoupled. Due to this reason a two degrees of freedom controller is considered [6].

A two degrees of freedom Pole placement controller using R, S and T polynomials has been implemented for a hot-dip galvanizing process. A methodology for the design and tuning of RST digital controllers that includes a brief description about the pole placement approach and its implementation is presented [7-9]. The RST controllers in discrete time to control the PWM rectifier, compressor and double star induction machine have been proposed [10-12]. RST controllers have been designed for a non uniform multi rate control system [13]. The purpose of this paper is to design various Digital RST controllers and to implement them for controlling the level in the process tank.

The paper is organized as follows: The level process station chosen for study is first described. The characteristics of the process components, the algorithm used for modelling and identification are highlighted. After validation of identified model, design of digital RST controllers are presented. Before providing the conclusion, the performance of these controllers using real time data are discussed.

II. PROCESS DESCRIPTION

The piping and instrumentation diagram of real time experimental level process setup is shown in Fig. 1 Pump(P) discharges the water from the Reservoir Tank(RT) to Over Head Tank(OHT). The Process Tank(PT) receives the water from the OHT. Flow rate is measured with Rotameter (R) at the inlet. An RF capacitance Level Transmitter(LT) is used to measure the level in the tank (0-20cm). The output current signal (4-20 mA) from LT is converted to corresponding digital value using a VUDAS100, USB based Data Acquisition card (DAQ) card which is interfaced with PC as shown in Fig. 4. The digital control algorithm is developed and configured in the controller which gives appropriate control signal. The controller output is given to digital to analog converter(DAC) in DAQ card is used to actuate motorized control valve (MCV). The inlet flow is manipulated by varying the stem position of the control valve in order to maintain the level of water in the process tank.

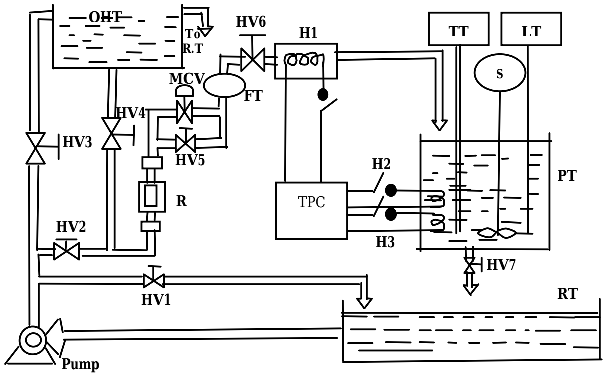

Fig. 1 Piping and Instrumentation diagram

HV-Hand valve; H-Heater; FT-Flow Transmitter; TT-Temperature Transmitter; S-Stirrer; TPC-Thyristor power control

A. *Characteristics of Process Components*

The characteristics of the motorized control valve is given in Fig. 2. The control valve used in this process is current to open valve type. For a variation of 4to 20mA current , the valve stem position gets displaced from 0.1 cm to 3 cm. Further the control valve stem movement behaves nonlinearly when the current range is between 4.1 and 12 mA, whereas it exhibits linear characteristics from 12.1 to 20 mA.

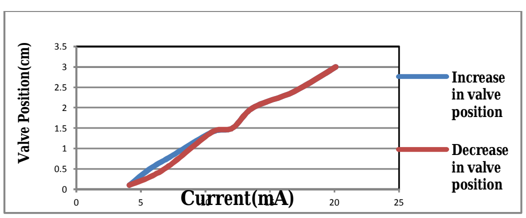

Fig. 2 Characteristics of the motorized control valve

The characteristics of DPT which outputs 4 to 20 mA for a variation in flow rate from 0 to 100 LPH is illustrated in Fig. 3.

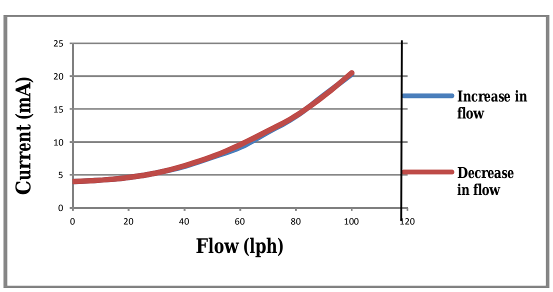

Fig. 3 Characteristics of the Differential pressure transmitter

III. Identification of the Process

System identification from the experimental data plays a vital role for the model based controller design. This work utilizes Black box modelling for identifying the chosen level process. Fig. 4 depicts the block diagram to interface level process setup using VUDAS 100 DAQ card to acquire open loop input- output data. The level in the tank varies depending upon the inflow rate. The entire operating range is split into three regions as (0.75-3.5cm), (3.5-7cm) and (7-9cm). For the first operating region, OR1, a 10% step change in manipulated variable (flow) is applied and the process is allowed to settle at 3.5 cm. Similar procedure is carried out for the next two regions, so that the process settles at 9cm finally and their corresponding open loop responses are obtained.

It is quite common to represent the input-output behavior of a continuous time system by transfer function in terms of laplace transform. The discrete time system are represented by pulse transfer function of the form,

$$H(z) = \frac{N(z)}{D(z)} \tag{1}$$

where N and D are polynomials given by

$$N(z) = 1 + a_1 z^{-1} + a_2 z^{-2} + \ldots a_n z^{-n} \tag{2}$$

$$D(z) = 1 + b_1 z^{-1} + b_2 z^{-2} + \ldots b_n z^{-m} \tag{3}$$

If the equivalent time description is considered, then a difference equation relating the output sequence $y(k)$ to the input sequence $u(k)$ can be obtained [5]. A backward-shift operator q^{-1} is used with the property as given in equation (4).

$$q^{-n} y(k) = y(k-n) \tag{4}$$

$$A(q^{-1})y(k) = B(q^{-1})u(k)$$

$$y(k) + \ldots + .a_n y(k-n) = b_0 u(k) + \ldots + b_m u(k-m) \tag{5}$$

The output $y(k)$ is given by

$$y(k) = -\sum_{j=1}^{n} a_j y(k-j) + \sum_{j=0}^{m} b_j u(k-j) \tag{6}$$

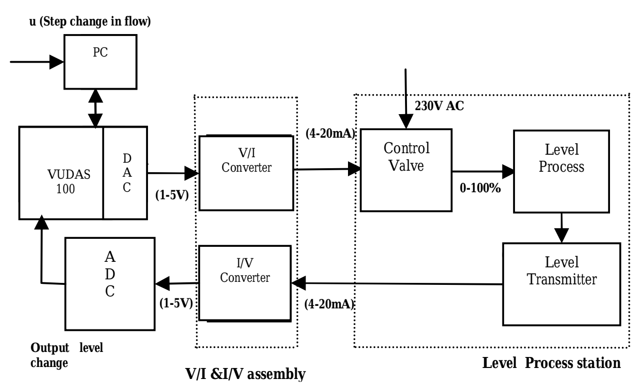

Fig. 4 Block diagram for interfacing level process with PC using VUDAS 100 DAQ card

Fig. 5 shows the sample open loop response for a 10% step change from 50-60% inflow rate for the operating region(OR2).

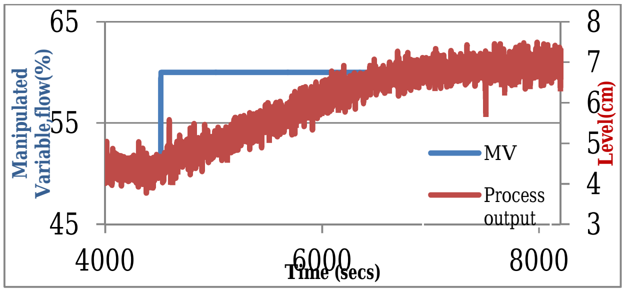

Fig. 5 Open loop response of the process(OR2)

A. *Identification using UD RLS Algorithm*

To obtain the model, Upper triangular-Diagonal Recursive Least Square(UD RLS) algorithm is used. It is based on recursive least square procedure and U-D factorization. U represents upper triangular and D represents diagonal matrix[2]. This algorithm requires fewer computations than the classical RLS.

$$\varepsilon(k) = y(k) - \hat{\theta}^T(k-1)\varphi(k) \tag{7}$$

$$G(K) = \frac{P(k-1)\varphi(k)}{\lambda + \hat{\varphi}(k)P(k-1)\varphi(k)} \tag{8}$$

$$P(k) = \frac{1}{\lambda}[1 - G(k)\varphi^T(k)P(k-1)] \tag{9}$$

$$\hat{\theta}(k) = \hat{\theta}(k-1) + G(k)\varepsilon(k) \tag{10}$$

The factorization is given as follows,

$$P(k) = U(k)D(k)U^T(k) \tag{11}$$

The identified discrete transfer function models for three operating regions are listed in Table I.

TABLE I
IDENTIFIED MODEL FROM UD RLS ALGORITHM

Operating region	Flow(lph)	Level(cm)	Identified model
1	48-52	0.75-3.5	$\frac{0.0004581}{z-0.9990}$
2	52 - 54	3.5 - 7.0	$\frac{0.0004657}{z-0.9992}$
3	54 - 58	7.0 - 9.0	$\frac{0.0004028}{z-0.9994}$

B. *Validation of Identified Model*

Model validation is a very important step before using it for designing a controller. Reliability of the obtained model depends on validation. Implementation of the model without validation may lead to erroneous and misleading results. So, it is essential to verify the model against plant operating data or experimental data. The time domain validation for a step change of 50-60% inflow(OR2) as given in Fig. 6 reveals that the response of the model tracks the actual response of the process.

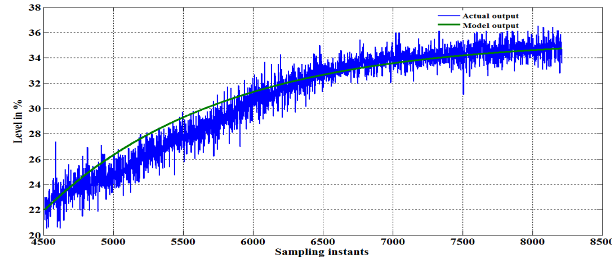

Fig. 6 Time domain validation for operating region 2

IV. DESIGN OF CONTROLLERS

The discrete canonical structure has two degrees of freedom, the digital filters R and S are designed in order to achieve the desired regulation performance, and the digital filter T is designed later so as to achieve the desired tracking performance [6-8]. Fig. 7 depicts the canonical structure of RST controller. This structure allows achievement of different levels of performance in tracking and regulation.

The equation of the RST canonical controller is given by

$$S(q^{-1})u(k) + R(q^{-1})y(k) = T(q^{-1})y^*(k+d+1) \tag{12}$$

where

$u(k)$ - Input of the plant
$y(k)$ - Output of the plant
$y^*(k+d+1)$ -Desired tracking trajectory

The polynomials $S(q^{-1})$, $R(q^{-1})$,$T(q^{-1})$ have the form,

$$R(q^{-1}) = r_0 + r_1 q^{-1} + \ldots.. + r_{n_R} q^{-n_R} \tag{13}$$

$$S(q^{-1}) = s_0 + s_1 q^{-1} + \ldots\ldots + s_{n_S} q^{-n_S} \tag{14}$$

$$T(q^{-1}) = t_0 + t_1 q^{-1} + \ldots.. + t_{n_T} q^{-n_T} \tag{15}$$

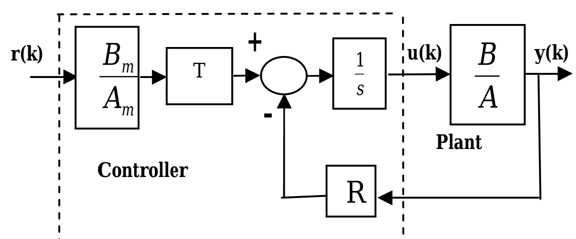

Fig. 7 Canonical structure of RST controller

A. *Digital RST-1 Controller*

Fig. 8 shows the block diagram of Digital RST-1 controller.

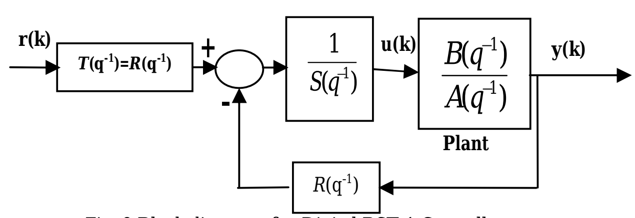

Fig. 8 Block diagram of a Digital RST-1 Controller

The pulse transfer function of the closed loop relating r(k) and the output y(k) is

$$H_{CL}(q^{-1})=\frac{B(q^{-1})R(q^{-1})}{A(q^{-1})S(q^{-1})+B(q^{-1})R(q^{-1})}=\frac{B(q^{-1})R(q^{-1})}{P(q^{-1})}=\frac{B_M(q^{-1})}{P(q^{-1})} \quad (16)$$

The coefficients of the polynomial $R(q^{-1})$ and $S(q^{-1})$ that represent the controller parameters are determined by solving the following equation.

$$P(q^{-1}) = A(q^{-1})S(q^{-1}) + B(q^{-1})R(q^{-1}) \quad (17)$$

Equation (17) is called Bezout polynomial equation, in which it is assumed that A and B polynomials are of the form,

$A(q^{-1}) = 1 + a_1 q^{-1} + .. + a_{n_A} q^{-n_A}$ replacing n_A by n in (2)

$B(q^{-1}) = b_1 q^{-1} + .. + b_{n_B} q^{-n_B}$ and n_B by m in (3)

The standard three branched structure can be implemented by considering $T(q^{-1})=R(q^{-1})$ in digital RST-1 controller[6],[8].

B. Digital RST-2 Controller

The block diagram of digital RST-2 controller is shown in Fig. 9. This is a digital PID that does not introduce additional zeros.

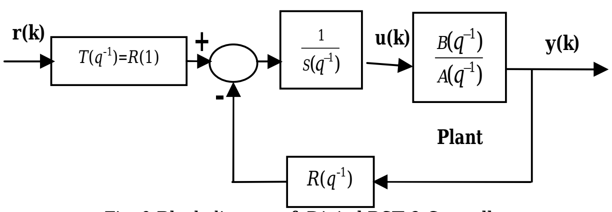

Fig. 9 Block diagram of Digital RST-2 Controller

The controller will have general structure as

$$S(q^{-1})u(k) + R(q^{-1})y(k) = T(q^{-1})r(k) \quad (18)$$

The closed loop transfer function using the controller specified by the equation (18) is

$$H_{CL}(q^{-1})=\frac{T(q^{-1})B(q^{-1})}{A(q^{-1})S(q^{-1})+B(q^{-1})R(q^{-1})}=\frac{[P(1)/B(1)]B(q^{-1})}{P(q^{-1})} \quad (19)$$

$$H_{CL}(q^{-1})=\frac{P(1)}{B(1)}\frac{B(q^{-1})}{P(q^{-1})}$$

in which $B(q^{-1})$ contains the plant zeros that will remain unchanged [6],[8]. $P(q^{-1})$ defines the desired closed loop poles and the term $P(1)/B(1)$ is introduced in order to ensure a unit gain between the reference and the output in steady state.

From equation (19)

$$T(q^{-1}) = \frac{P(1)}{B(1)} = \frac{B(1)R(1)}{B(1)} = R(1) \quad (20)$$

Since S(1)=0 (which implies $P(1)=B(1)R(1)$). Then $T(q^{-1})$ will be a gain equal to the sum of the co-efficient of R(q^{-1}). The only difference from RST1 controller is that now $T(q^{-1}) = R(1)$ instead of $R(q^{-1})$, thereby preserving the unitary gain of the closed loop system in steady state without however introducing the effect of the zeros of $R(q^{-1})$.

C. *Digital RST-3 controller*

The transfer function of the process is

$$H(q^{-1}) = \frac{B(q^{-1})}{A(q^{-1})} = \frac{b_1 q^{-1}}{1 + a_1 q^{-1}} \quad (21)$$

The desired closed loop reference model be

$$H_m(q^{-1}) = \frac{B_m(q^{-1})}{A_m(q^{-1})} = \frac{b_{m1} q^{-1}}{1 + a_{m1} q^{-1}} \quad (22)$$

The desired closed loop operator (β) is thus given by

$$H_m(q) = \beta \frac{b_1}{q + a_{m1}} \quad (23)$$

where

$\beta = \frac{1 + a_{m1}}{b_1}$ which gives a unit steady state gain[15].

The diaphantine equation AR+BS=A_c becomes

$$(q + a_1)r_0 + b_1 s_0 = 1(q + a_{m1}) \quad (24)$$

$$qr_0 + a_1 r_0 + b_1 s_0 = q + am_1$$

Equating co-efficient of q^0 in equation (24) gives

$$r_0 = 1$$

rearranging equation (24), it gives

$$s_0 = \frac{a_{m1} - a_1}{b_1}$$

For first order process, the R,S and T polynomials are as follows,

$$R(q^{-1}) = r_0 \text{ , } S(q^{-1}) = s_0 \text{ and } T(q^{-1}) = \beta(a_1)$$

D. RST controller based on Pole Placement

The structure of the closed loop system with pole placement controller is given in Fig. 10.

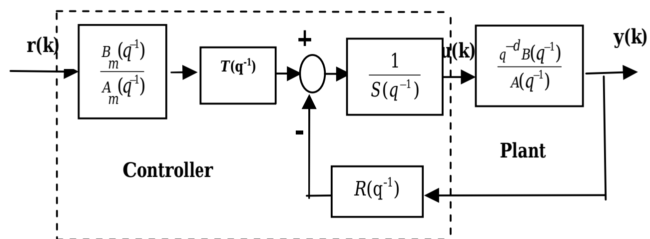

Fig. 10 Block diagram representation of a closed loop system with pole placement controller

The plant to be controlled is characterized by the pulse transfer function,

$$H(q^{-1}) = \frac{q^{-d} B(q^{-1})}{A(q^{-1})} \quad (25)$$

in which d is the integer number of sampling periods contained in time delay.

The closed loop transfer function is given by

$$H_{CL}(q^{-1}) = \frac{q^{-d} T(q^{-1}) B(q^{-1})}{P(q^{-1})} \quad (26)$$

in which, $P(q^{-1}) = A(q^{-1})S(q^{-1}) + q^{-d} B(q^{-1})R(q^{-1}) = 1 + p_1^{'} q^{-1} + p_2^{'} q^{-2}$ (27)

Equation (27) defines the closed loop poles that plays an essential role for the regulation behaviour [7-8],[14].

V. SIMULATION RESULTS AND DISCUSSION

A. Design of RST Polynomial Coefficients (with first order reference model)

The identified process using UD RLS algorithm is first order process. The desired first order reference model chosen for the identified process is given in equation (28). Sampling time is taken as 1 sec.

$$\frac{B_m(q^{-1})}{A_m(q^{-1})} = \frac{b_{m1}q^{-1}}{1 + a_{m1}q^{-1}} = \frac{0.4\,q^{-1}}{1 - 0.5990\;q^{-1}} \qquad (28)$$

The reference model is selected to have open loop gain and time constant approximately equal to 1 and 2 respectively. Various RST polynomials with first order reference model for three operating regions are listed in Table II.

TABLE II
VARIABLE RST POLYNOMIALS

Operating Range(cm)	Controllers	Polynomials
0.75 - 3.5	Digital RST-1	$R(q^{-1}) = 2206.2 - 1523.3q^{-1}$ $S(q^{-1}) = 1 - q^{-1}$ $T(q^{-1}) = 2206.2 - 1523.3q^{-1}$
	Digital RST-2	$R(q^{-1}) = 2206.2 - 1523.3q^{-1}$ $S(q^{-1}) = 1 - q^{-1}$ $T(q^{-1}) = 682.9132$
	Digital RST-3	$R(q^{-1}) = 1$ $S(q^{-1}) = 3488.321$ $T(q^{-1}) = 3487.01$
	Pole Placement	$R(q^{-1}) = 3052.1 - 2180.7q^{-1}$ $S(q^{-1}) = 1 - q^{-1}$ $T(q^{-1}) = 2182.9 - 1307.6q^{-1}$
3.5 - 7	Digital RST-1	$R(q^{-1}) = 3006.7 - 2145.6q^{-1}$ $S(q^{-1}) = 1 - q^{-1}$ $T(q^{-1}) = 3006.7 - 2145.6q^{-1}$
	Digital RST-2	$R(q^{-1}) = 3006.7 - 2145.6q^{-1}$ $S(q^{-1}) = 1 - q^{-1}$ $T(q^{-1}) = 861.06$
	Digital RST-3	$R(q^{-1}) = 1$ $S(q^{-1}) = 3431.8$ $T(q^{-1}) = 3430.8$
	Pole Placement	$R(q^{-1}) = 3006.7 - 2145.6q^{-1}$ $S(q^{-1}) = 1 - q^{-1}$ $T(q^{-1}) = 2147.3 - 1286.2q^{-1}$
7 - 9	Digital RST-1	$R(q^{-1}) = 3476.7 - 2481.1q^{-1}$ $S(q^{-1}) = 1 - q^{-1}$ $T(q^{-1}) = 3476.7 - 2481.1q^{-1}$
	Digital RST-2	$R(q^{-1}) = 3476.7 - 2481.1q^{-1}$ $S(q^{-1}) = 1 - q^{-1}$ $T(q^{-1}) = 995.53$
	Digital RST-3	$R(q^{-1}) = 1$ $S(q^{-1}) = 3488.321$ $T(q^{-1}) = 3487.01$
	Pole Placement	$R(q^{-1}) = 3476.7 - 2481.1q^{-1}$ $S(q^{-1}) = 1 - q^{-1}$ $T(q^{-1}) = 2482.6 - 1487.1q^{-1}$

B. Process Response with Proposed controllers for OR1

Fig. 11 shows the closed loop response of the process for the operating range 0.75-3.5 cm when implementing various RST controllers. Performance of the process with RST-2 and RST-3 controller tries to track the reference(ref) trajectory almost closely without overshoot whereas RST-1 cannot provide the same. A disturbance (d) of 0.5 cm is given at 53 sec. Pole placement (PP) controller rejects the disturbance faster compared to other controllers. The corresponding controller outputs are shown in Fig. 12.

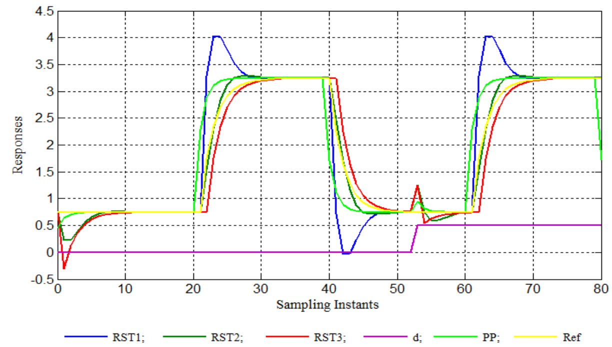

Fig. 11 Closed loop response of the process with proposed controllers for OR1

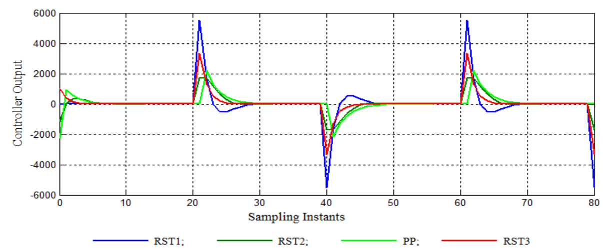

Fig. 12 Plots of the controller output for OR1

C. Process Response with Proposed controllers for OR2

Fig. 13 presents the behaviour of the process for the operating range 3.5-7cm when implementing the newly proposed controllers. It can be observed that performance with RST-2 and RST-3 controllers settles to reference value without overshoot, whereas RST-1 controller cannot provide the same. Also the performance of the chosen process for Pole placement controller is still more undesirable as it is sluggish.

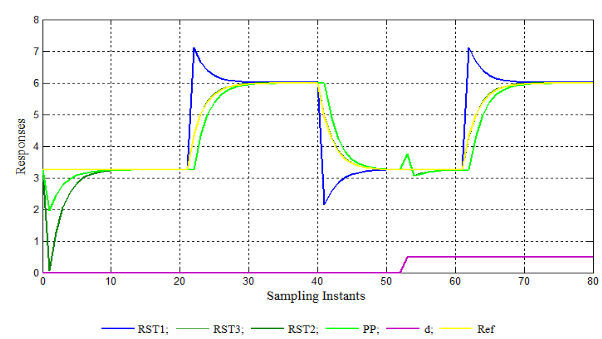

Fig. 13 Closed loop response of the process with proposed controllers for OR2

The corresponding controller outputs are shown in Fig. 14.

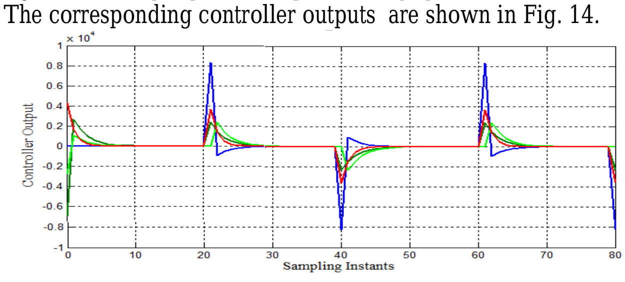

Fig. 14 Plots of the controller output for OR2

D. *Process Response with Proposed controllers for OR3*

Proceeding further and implementing these controllers for OR3, the performance of the chosen process is plotted as shown in Fig. 15. It is inferred that RST-2 controller closely matches with the reference whereas the other controllers cannot provide. Also the performance of PP controller is still sluggish and has delay. A disturbance of 0.5 cm is given at 53 sec. Pole placement controller rejects the disturbance faster compared to other controllers.

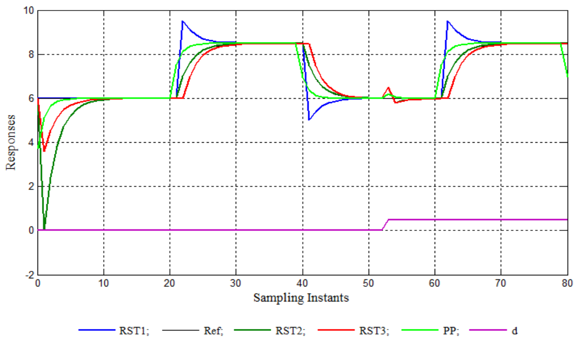

Fig. 15 Closed loop response of the process with proposed controllers for OR3

The corresponding controller outputs are shown in Fig. 16.

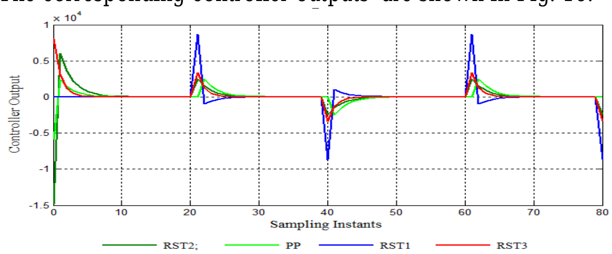

Fig. 16 Plots of the controller output for OR3

The performance of the chosen process while implementing the various proposed digital RST controllers can be compared by computing the values of three time integral criteria such as Integral Square Error(ISE), Integral Absolute Error(IAE) and Integral Time Absolute Error(ITAE) and are presented in Table III.

TABLE III

TIME INTEGRAL CRITERIA VALUES FOR VARIOUS OPERATING REGIONS

Operating Region(cm)	**Controllers**	**Time Integral Criteria**		
		ISE	**IAE**	**ITAE**
0.75 - 3.5	Digital RST-1	23.91	19.97	879.6
	Digital RST-2	1.59	6.524	231.7
	Digital RST-3	14.21	15.88	621.4
	Pole Placement	6.72	11.1	383.7
3.5 - 7	Digital RST-1	35.81	22.05	960.4
	Digital RST-2	16.59	9.66	103.7
	Digital RST-3	18.19	18.96	694.4
	Pole Placement	8.674	12.47	417
7 - 9	Digital RST-1	29.77	20.46	888.8
	Digital RST-2	56.2	16.71	132.5
	Digital RST-3	18.79	20.11	645.7
	Pole Placement	13.99	14.49	393.1

VI. CONCLUSION

This paper has dealt with the design and implementation of various RST controllers such as Digital RST-1,RST-2, RST-3 and pole placement controller for a chosen level process. Open loop data are acquired in real time by interfacing MATLAB through VUDAS100 DAQ card for identification purpose. A recursive least square estimation algorithm with UD factorization is used to identify the process. The digital RST-2 controller is able to provide efficient reference tracking with disturbance rejection for the chosen operating regions. It is also observed that the time integral error criteria values of digital RST-2 and pole placement controller are less when compared with performance of other two controllers. It is further concluded that the performances of the process with RST-2 and RST-3 controllers closely match with the reference trajectory.

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