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Design and Implementation of LabVIEW Based Optimally Tuned PI Controller for A Real Time Non Linear Process

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ABSTRACT

The phenomenal growth that has been evidently seen in the last two decades has brought a multifold development in the process industry. The experts have always focused upon the control of the level and other process parameters. In this study we have chosen a real time Single Spherical Tank Liquid Level System (SSTLLS) for our investigation. The aim of this study is to compare the design and implementation of different PI controllers for the SSTLLS using LabVIEW and NI-DAQmx 6211 data acquisition card. The real time model identification and Graphical User Interface (GUI) are discussed and their PI controller implementation using LabVIEW are outlined.

Key words: Single spherical tank liquid level system, graphical user interface, PI controller, Chen-Hrones-Reswick method, skogested internal model controller tuning, Zhuang-Atherton method, LabVIEW

INTRODUCTION

In common terms, most of the industries have typical problems raised because of the dynamic non linear behaviour. It's only because of the inherent non linearity, most of the chemical process industries are in need of classical control techniques. Hydrometallurgical industries, food process industries, concrete mixing industries and waste water treatment industries have been actively using the spherical tanks as an integral process element. Due to its changing cross section and non linearity, a spherical tank provides a challenging problem for the level control.

Liquid level control systems have always pulled the attention of industry for its very important manipulated parameter of level which finds many applications in various fields. An accurate knowledge of an adequate model is often not easily available. An insufficiency in this aspect of model design can always lead to a failure in some non linear region with higher non linearity. The evidence that many researchers are working in the nonlinear models and their controlling strategies (Biegler and Rawlings, 1991; Kravaris and Arkun, 1991) which in turn explained about the process dynamics around a larger operating region than the corresponding linear models have been gaining great popularity (Raich *et al*., 1991). The non linear models are obtained from first principles and further from the parameters which appear within such models that are obtained from the data of the process. However the conventional methods for developing such models are still in search. Once the model has been developed, then the need for the controller design comes in to picture to maintain the process under steady state. Proportional Integral Derivative (PID) controller is the name that is widely heard as a part of the process control industry. Despite much advancement in control theory which has been recently seen, PID controllers are still extensively used in the process industry. Conventional PID controllers are simple, inexpensive in cost (Mann *et al.*, 1999), easy to design and robust provided the system is linear. The PID controller operates with three parameters which can be easily tuned by trial and error, or by using different tuning strategies and rules available in literature (Ziegler and Nichols, 1942; Zhuang and Atherton, 1993; Sung *et al.*, 1996). These rules have their bases laid on open-loop stable first or second order plus dead time process models. There are many other methods and approaches which have periodically evolved to improvise the performance of PID tuning. For instance the Astrom-Hagglund phase margin method (Astrom and Hagglund, 1984), the refined ZN method by Cohen and Coon (1953) as well as Hang *et al.* (1991), the Internal Model Control (IMC) design method (Garcia and Morari, 1982; Rivera *et al.*, 1986), gain and phase margin design methods (Hagglund and Astrom, 1996; De Paor and O'Malley, 1989) and so on. The software and technology have been assisting the mankind to design and implement more sophisticated control algorithms. Despite all the effort, industries emphasize more on robust and transparent process control structure that uses simple controllers which makes PID controller the most widely implemented controller.

SSTLLS has been a model for quite a many experiments performed in the near past. Nithya *et al.* (2008) have designed a model based controller for a spherical tank which gave a comparison between IMC and PI controller using MATLAB. Nandola and Bhartiya (2008) have studied and mathematically designed a predictive controller for non linear hybrid system. A model reference adaptive controller has been designed and simulated by Krishna *et al.* (2012) for a spherical tank. A gain scheduled PI controller was designed using a simulation on MATLAB for a second order non linear system by Kumar and Meenakshipriya (2012) which gave information about servo tracking for different set points. A fractional order PID controller was designed for liquid level in spherical tank using MATLAB which compared the performance of fractional order PID with classical PI controller by Sundaravadivu and Saravanan (2012). Chakravarthi *et al.* (2014) have implemented a classical and gain scheduled PI controllers for a single and dual spherical tank systems in real time using LabVIEW (Chakravarthi and Venkatesan, 2014; Chakravarthi *et al.*, 2014). Soni *et al.* (2014) have simulated and studied the performance of multi model PI controller for SSTLLS using MATLAB.

This study endeavours to design a system using the process reaction curve method which is also known as first principle method. We obtain model of the plant experimentally for a given unit-step input. If the plant involves neither integrator(s) nor dominant complex-conjugate poles, then such a unit step response curve may look S-shaped curve as shown in Fig. 1. Such step response curve

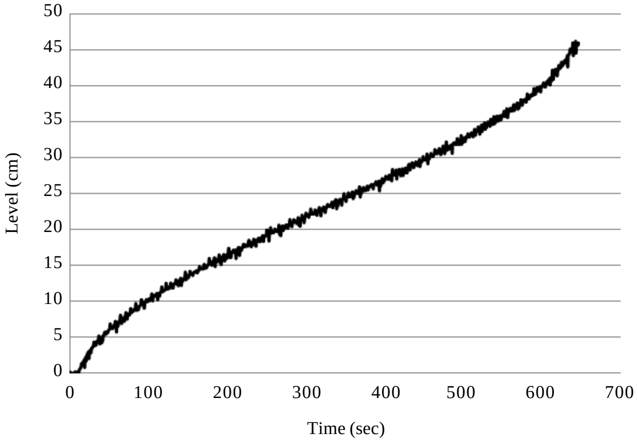

Fig. 1: S-shaped open loop input-output response curve

may be generated experimentally or from a dynamic simulation of the plant. The S-shaped curve may be characterized by two constants, delay time L and time constant τ. After deriving the model, we implement the CHR tuning, SIMC tuning, ZA tuning techniques to design the PI controller so as to control the level parameter of the SSTLLS in real time using the data acquisition card in LabVIEW environment.

METHODOLOGY

Experimental process description: The laboratory set up for this system basically consists of two spherical interacting tanks which are connected with a manually operable valve between them. Both the tanks have an inflow and outflow of water which is being pumped by the motor which continuously feeds in the water from the water reservoir. The flow is regulated in to the tanks through the pneumatic control valves, whose position can be controlled by applying air to them. A compressor so as to apply pressure to close and open the pneumatic valves was used. There is also provision given to manually measure the flow rate in both the tanks using rotameter. The level in the tanks are being measured by a differential pressure transmitter which has a typical output current range of 4-20 mA. This differential pressure transmitter is interfaced to the computer connected through the NI-DAQmx 6211 data acquisition card which can support 16 analog inputs and 2 analog output channels with a voltage ranging between ±10 V. The sampling rate of the acquisition card module is 250 Ks/S with 16 bit resolution. The graphical program written in LabVIEW is then linked to the set up through the acquisition module. Figure 2 shows the real time experimental setup of the process.

The process of operation starts when pneumatic control valve is closed by applying the air to adjust the flow of water pumped to the tank. This study talks only about a Single Spherical Tank Liquid Level System (SSTLLS), so we shall use only the spherical tank one for our usage throughout the experiment. The level of the water in tank is measured by the differential pressure transmitter and is transmitted in the form of current range of 4-20 mA to the interfacing NI-DAQmx 6211 data acquisition module card to the Personal Computer (PC). After computing the control algorithm in the PC, control signal is transmitted to the I/P converter which passes the pressure to the pneumatic valve proportional to the current provided to it. The pneumatic valve is

Fig. 2: Real time experimental set up of the process

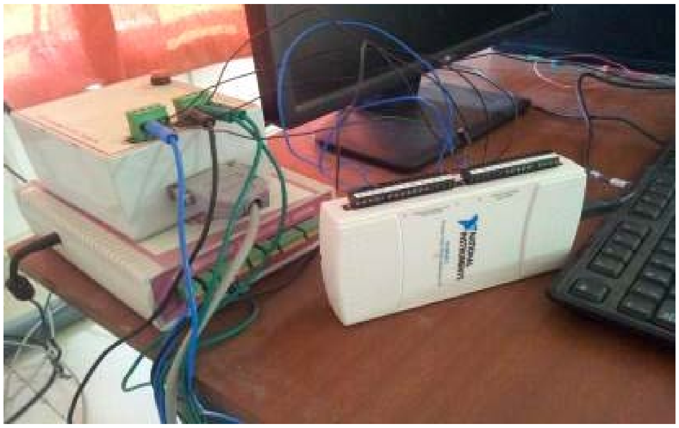

Fig. 3: Interfaced NI-DAQmx 6211 data acquisition module card

Table 1: Technical specifications of the experimental setup

Part name	Details
Spherical tank	Material: Stainless steel
	Diameter: 45 cm
Storage tank	Material: Stainless steel
	Volume: 100 L
Differential pressure transmitter	Type: Capacitance
	Range: 2.5 to 250 mBAR
	Output: 4 to 20 mA
Pump	Centrifugal 0.5 HP
Control valve	Size: 1/4", Pnematic actuated
	Type: Air to close
	Input: 3-15 PSI
	0.2-1 kg cm^{-2}
Rotometer	Range: 0-440 LPH
Air regulator	Size: 1/4" BSP
	Range: 0-2.2 BAR
I/P converter	Input: 4-20 mA
	Output: 3-15 PSI
Pressure gauge	Range: 0-30 PSI
	Range: 0-100 PSI

actuated by the signal provided by I/P converter which in turn regulates the flow of water in to the tank. Figure 3 shows the interfaced NI-DAQmx 6211 data acquisition card. Table 1 shows the technical specifications of the interacting two tank spherical tank liquid level system setup. A graphical user interface of the SSTLLS which is designed by using LabVIEW, can also be seen in Fig. 4.

System identification and controller design

Mathematical modelling of SSTLLS: The SSTLLS is a system which is non linear in nature by virtue of its varying diameter. The dynamics of this non linearity can be described by the first order differential equation:

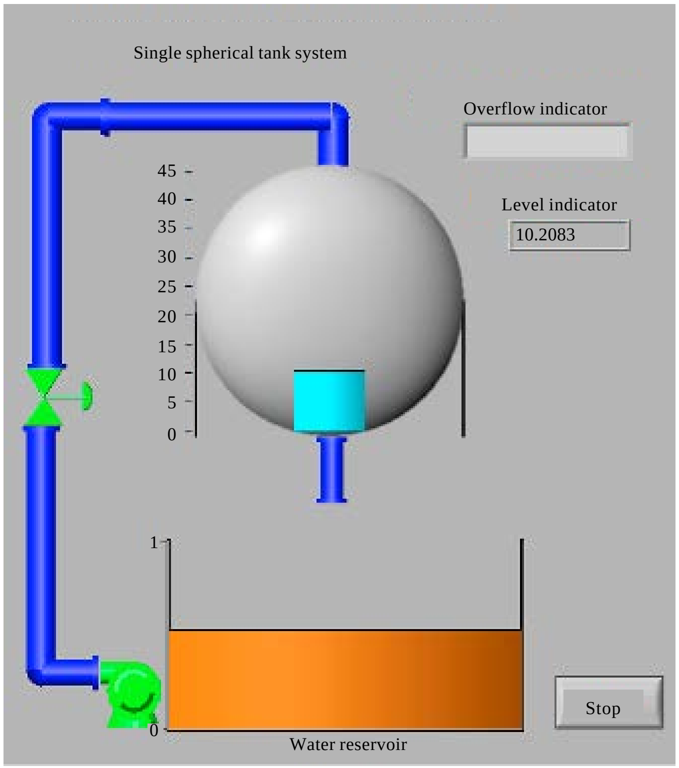

Fig. 4: Graphical user interface for the SSTLLS designed in LabVIEW

$$\frac{dV}{dt} = q_1 - q_2 \qquad (1)$$

where, V is the volume of the tank, q_1 is the inlet flow rate and q_2 is the outlet flow rate.

The volume V of the spherical tank is given by:

$$V = \frac{4}{3}\pi h^3 \qquad (2)$$

where, h is the height of the tank in centimeter.

On application of the steady state values and by solving the Eq. 1 and 2, the non linear spherical tank can be linearized to the following model:

$$\frac{H(S)}{Q1(S)} = \frac{Rt}{\tau s + 1} \qquad (3)$$

where, $\tau = 4\pi R_t h_S$ and:

$$Rt = \frac{2hs}{Q2s}$$

The system identification of SSTLLS is derived using the black box modelling. Under constant inflow and constant outflow rates of water, the tank is allowed to fill from 0-45 cm. Each sample is acquired by NI-DAQmx 6211 from the differential pressure transmitter through USB port in the range of 4-20 mA and the data is transferred to the PC.

This data is further scaled in terms of level in centimeter. Employing the open loop method, for a given change in the input variable; the output response of the system is recorded. Ziegler and Nichols (1942) have obtained the time constant and time delay of a FOPDT model by constructing a tangent to the experimental open loop step response at its point of inflection. The intersection of the tangent with the time axis provides the estimate of time delay. The time constant is estimated by calculating the tangent intersection with the steady state output value divided by the model gain.

Cheng and Hung (1985) have also proposed tangent and point of inflection methods for estimating FOPDT model parameters. The major disadvantage of all these methods is the difficulty in locating the point of inflection in practice and may not be accurate. Prabhu and Chidambaram (1991) have obtained the parameters of the first order plus time delay model from the reaction curve obtained by solving the nonlinear differential equations model of a distillation column.

Sundaresan and Krishnaswamy (1978) have obtained the parameters of FOPDT transfer function model by collecting the open loop input-output response of the process and that of the model to meet at two points which describe the two parameters τ_p and θ. The proposed times t_1 and t_2, are estimated from a step response curve. The proposed times t_1 and t_2, are estimated from a step response curve. This time corresponds to the 35.3 and 85.3% response times.

The time constant and time delay are calculated as follows:

$$\tau_p = 0.67(t_2\text{-}t_1) \tag{4}$$

$$\theta = 1.3t_1\text{-}0.29t_2 \tag{5}$$

At a constant inlet and outlet flow rates, the system reaches the steady state. After that a step increment is given by changing the flow rate and various values of the same are taken and recorded till the system becomes stable again as shown in the Fig. 1. The experimental data are approximated to be a FOPDT model. The model parameters are identified for SSTLLS to be:

$$G(s) = \frac{15.e^{-82.94s}}{265.15s+1} \tag{6}$$

Design of PI controller: The derivation of transfer function model will now pave the way to the controller design which shall be used to maintain the system to the optimal set point. This can be only obtained by properly selecting the tuning parameters K_p and K_i for a PI controller.

The conventional FOPDT model is given by:

$$G(s) = \frac{K.e^{-\theta s}}{\tau s+1} \tag{7}$$

By implementing the rules of PI tuning by the CHR tuning, SIMC tuning, ZA tuning methods to get the above said parameters for the transfer function specified in Eq. 6. Table 2 gives the values of the derived, for the respective tuning methods used in this study.

RESULTS AND DISCUSSION

The CHR tuning, SIMC tuning, ZA tuning based PI controllers which were designed are implemented using the graphical programming code which is written on LabVIEW. All the controllers with their respective tuned methods were applied to SSTLLS and the performance of the both was compared under different conditions.

Variation of the set point: The CHR tuning, SIMC tuning, ZA tuned controllers are run for a sequence of set points which are 5, 15, 25, 30 and 45 cm and their performance is compared with each other for the same sequence of set points. The level varies for both the controllers and their changes are seen in the Fig. 5a. Figure 5b-f demonstrate the servo response characteristics of the set point change profile for 5, 15, 25, 30 and 45 cm, respectively. Table 3 evidently demonstrates the time indices for the varying set profiles said above. It can be seen that for the lower non linear ranges between 0 and 5 cm of height in the system ZA method of tuning gives faster rise time, settling time and peak time when compared to that of CHR and SIMC methods, because of relatively lower K_i values account for this outcome. CHR method of tuning proves to be better, with respect to the time indices in all the other set points. The settling time shows a typical variation in

Table 2: Tuned PI controller parameters for CHR tuning, SIMC tuning, ZA tuning methods

Type of controller	K_P	K_i
CHR tuning	0.07459	0.000234427
SIMC tuning	0.213126	0.000803794
ZA tuning	0.01715129	0.000173037

Table 3: Comparison of time domain indices for servo response at different set points

Specifications and set point	ZA	CHR	SIMC
Rise time (sec)			
0-5	71.97187	72.1125	72.37969
5-15	112.9922	81.675	114.4687
15-25	130.8093	130.95	134.5921
25-30	87.34221	69.13125	97.4812
30-45	89.38125	94.10625	99.09846
Peak time (sec)			
0-5	79.96875	80.125	80.42188
5-15	125.5469	90.750	127.1875
15-25	145.3437	145.50	149.5468
25-30	97.0469	76.8125	108.3125
30-45	99.3125	104.5625	110.1094
Settling time (sec)			
0-5	0.750	0.59375	0.29687
5-15	2.3906	37.1875	0.750
15-25	11.8594	11.7031	7.6563
25-30	11.5625	31.7969	0.750
30-45	55.6406	50.3906	45.8437

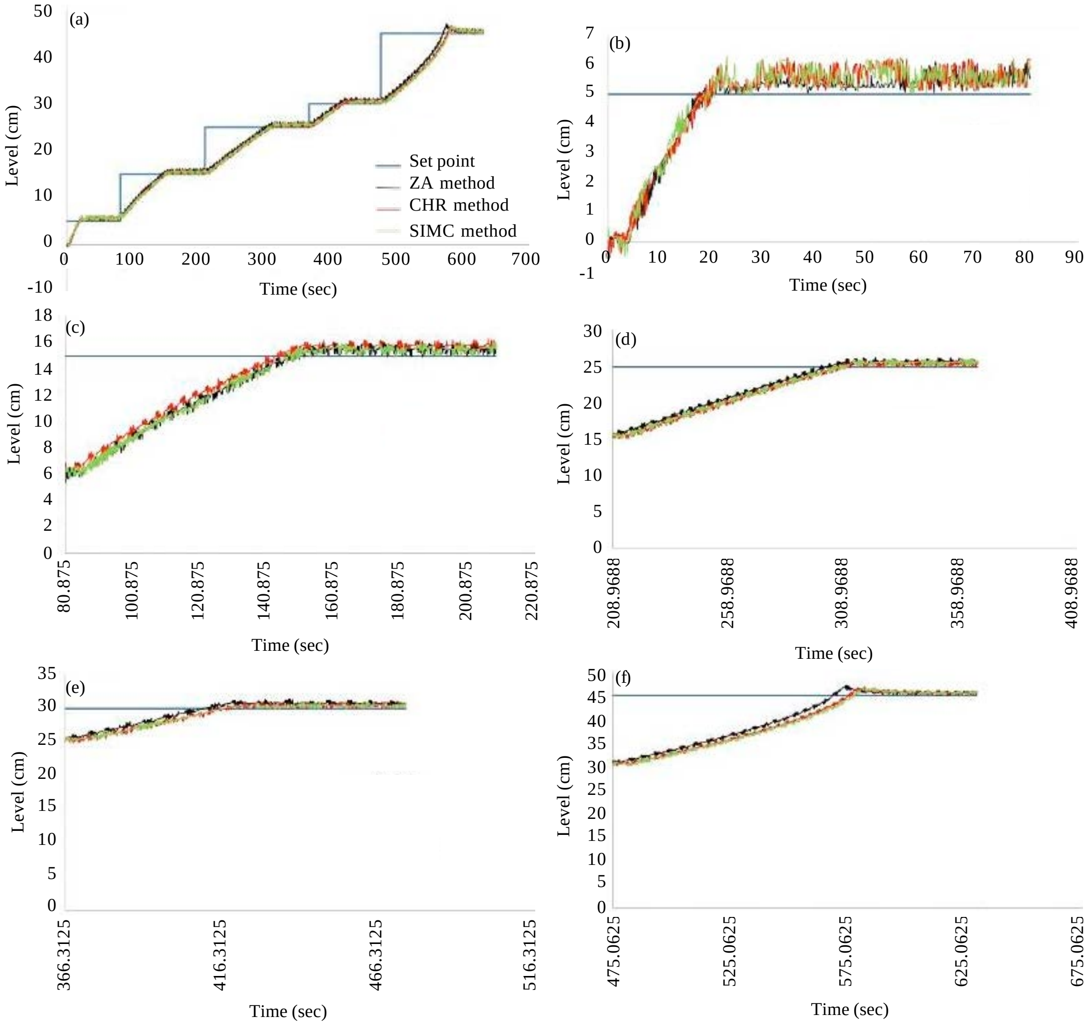

Fig. 5(a-f): Comparison of servo responses CHR tuning, SIMC tuning, ZA tuning based PI tuned controllers for a set point change (a) Control, (b) 5 cm, (c) 15 cm, (d) 25 cm, (e) 30 cm and (f) 45 cm

the case of SIMC method for all the changes set points. SIMC gives a very less value of settling time for all the set points in varying regions of non linearity. Table 4 deals with the performance indices like ISE, IAE, ITAE for the different set points in the entire region of operation. It can be observed that ISE, IAE and ITAE values for the ZA method in non linear region of 5 cm is less when compared to that CHR and SIMC method. If keenly observed SIMC tuned controller performs better than that of other two methods with respect to ISE, IAE and ITAE calculations. It can be inferred that for faster time response in non linear regions ZA method of tuning proves to be the best method. But if the emphasize is more on the error reduction in the system, SIMC method gives a best of its performance in almost all the regions of operations.

Changes in load: The CHR tuning, SIMC tuning, ZA tuned controllers have been used to control the level of SSTLLS while applying a load change of 7.5% for a set of set points. Initially to test the

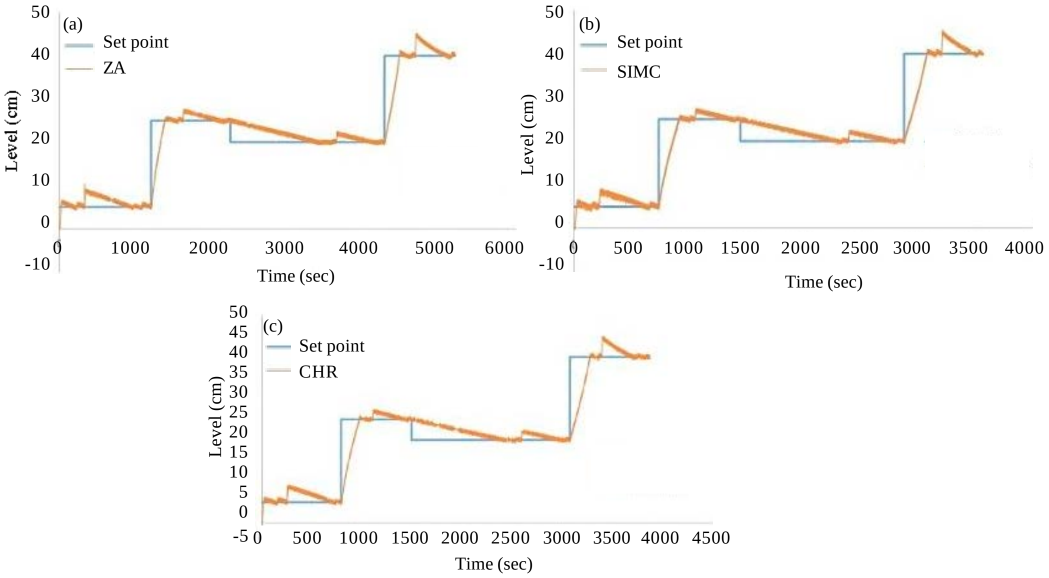

Fig. 6(a-c): Regulatory response using (a) ZA tuned controller, (b) SIMC tuned controller and (c) CHR tuned controller

Table 4: Comparison of performance indices for servo response at different set points

Specification and set point	ZA	CHR	SIMC
ISE			
0-5	80.87573	196.0458	186.4216
5-15	240.2060	116.1236	116.9536
15-25	226.2085	76.62538	154.9183
25-30	261.0747	123.9311	106.7335
30-45	224.9570	187.5046	186.6177
IAE			
0-5	160.3645	248.3581	244.9153
5-15	303.2945	193.7417	196.1724
15-25	291.9027	153.6155	226.5198
25-30	314.7378	201.9683	187.0507
30-45	259.5278	231.9611	227.1456
ITAE			
0-5	8868.75	12742.39	12472.36
5-15	54127.70	34789.36	35145.33
15-25	98066.98	51934.64	76618.46
25-30	139936.6	90320.13	83689.16
30-45	153983.6	138835.2	136277.9

response of the tank in its non linear region, a set point of 5 cm was fed to the program and the readings were recorded. Similar method was employed for the set points of 25, 20 and 40 cm, respectively. At all the levels, a disturbance is added to the system to observe its performance. After 25 cm a negative set point change of 20 cm was also given. From the Fig. 5 and 6a-c the regulatory load change and the set point tracking under the influence of external disturbance for CHR tuning, SIMC tuning, ZA tuning based PI controllers, respectively can be observed. The performance indices of the regulatory response is given in Table 5. The designed controllers were able to

Table 5: Comparison of performance indices for regulatory response at different set points

Specifications and set point	ZA	CHR	SIMC
ISE			
0-5	2081.853	1666.16	1364.222
5-25	6242.667	3064.112	3388.292
20-45	17968.46	13225.29	13238.23
IAE			
0-5	9482.406	7081.325	6145.408
5-25	4519.555	2510.313	2654.566
20-45	6248.669	4876.894	4645.26
ITAE			
0-5	5029157	2787291	2146949
5-25	8032005	3041881	3077890
20-45	30164115	17032128	15317184

compensate the effect of the load changes. It can be noticed from Table 5, that the ISE, IAE and ITAE values for CHR tuned controller are lesser than that of ZA and SIMC methods, for all the regions of operation, except the lower most region of operation. SIMC method shows a better performance in the lower most region with lower ISE, IAE and ITAE values.

CONCLUSION

In this study, CHR, SIMC, ZA tuned controllers have been designed and implemented to control the level of SSTLLS process. The model identification and controller design were done using an NI-DAQmx 6211 data acquisition card and LabVIEW. Graphical programming was used to implement the whole experiment. The experimental results evidently prove that the influence of set point and load changes have expressed different patterns for different regions of non linearity. During the regulatory tracking, the ISE, IAE and ITAE values for CHR tuned controller are lesser than that of ZA and SIMC methods, for all the regions of operation, except the lower most region of operation. SIMC method shows a better performance in the lower most region with lower ISE, IAE and ITAE values. During the servo tracking, if keenly observed SIMC tuned controller performs very better than that of other two methods with respect to ISE, IAE and ITAE calculations. It can be inferred that for faster time response in non linear regions ZA method of tuning proves to be the best method. But if the emphasize is more on the error reduction in the system, SIMC method gives a best of its performance in almost all the regions of operations. It can be concluded that SIMC tuned controller provides a very good error rejection in the lower regions of SSTLLS, i.e., higher degree of non linearity, while ZA tuned controller can be employed for all other regions of SSTLLS using NI-DAQmx 6211 data acquisition module and LabVIEW.

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